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THE STELLAR SPECTROGRAPH OF THE 72-INCH
REFLECTING TELESCOPE

BY J. S. PLASKETT

The telescope has been described in two issues of the *Journal of the Royal Astronomical Society of Canada* and in the *Publications of the Astronomical Society of the Pacific* for October, 1918, but it seems advisable to summarize the principal optical and operating details of this light-gatherer for the spectrograph.

The aperture of the principal mirror is 184.5 cm (72.6 in.) and its focal length 917.9 cm (361.38 in.). It has a central hole 25.7 cm (10.13 in.) in diameter which allows the spectrograph, which is used with the Cassegrain form of the telescope, to be placed along the axis of the mirror and attached to the bottom of the tube, a much more convenient and symmetrical position than if a third reflection were used and the spectrograph were attached to the side of the tube. The Cassegrain mirror is 50.8 cm (20 in.) in diameter, has a radius of curvature of 605.6 cm (19.87 ft.), and is placed about 218 cm (7.15 ft.) inside the principal focus of the main mirror. The equivalent focal length of the combination is approximately 32.92 meters (108 ft.), and the aperture ratio is reduced from 1:5 to 1:18.

Tests of the figure of the principal mirror in the optical shop under constant-temperature conditions showed a maximum

longitudinal aberration of 0.25 mm (0.01 in.) and this, being for a median zone, is equivalent to lateral aberration 0.025 mm to a circle of confusion of less than the thousandth of an inch in diameter. Under changing conditions of temperature in the dome this is much increased, and after a daytime rise of 5° C. the aberration, under-correction, became about 3 mm. The application of heat-insulating covers to the lower end of the tube completely inclosing the mirror reduced the temperature change to less than one-third that in the dome, with the result that, as the nocturnal change of temperature is very small and slow, the working figure remained practically perfect, and the longitudinal aberration, always under-correction, was of the order of 0.5 mm.

The figure of the Cassegrain combination has recently been tested by the Hartmann method. The figure is also very good, the effective aberration under average observing conditions being about 1.5 mm, equivalent to a circle of confusion 0.05 mm in diameter. This is an example of the skill of Mr. J. B. McDowell, of the John A. Brashear Co., Ltd., as this mirror was corrected in combination with the 72-inch while only a 33-inch plane was available for producing a parallel pencil. Hence less than one-half the diameter, one-fourth the area, of the secondary could be tested at a time, and the difficulty of figuring was thereby much increased.

The general form of the mounting and the appearance and position of the spectrograph can be seen in Plate XII. The mounting is beautifully designed and constructed and is undoubtedly the most perfect and complete of any hitherto made by the Warner & Swasey Co. The driving is perfect, without a trace of periodic or other error, which is so frequent a source of trouble and annoyance in telescopes. The following is so close, the figure of the mirrors and generally the seeing so good, that it is necessary to set the clock driving slightly fast or slow, else the image remains so nearly in one position on the slit, which subtends an angle of 0".3 by 3", as to produce too narrow or unevenly exposed spectra.

The arrangements for quick and fine setting of the telescope are very convenient, so that little time is lost in changing from star to star in spectroscopic observation. There are three speeds in each co-ordinate, all electrically driven, a quick motion of 45° to

PLATE XII
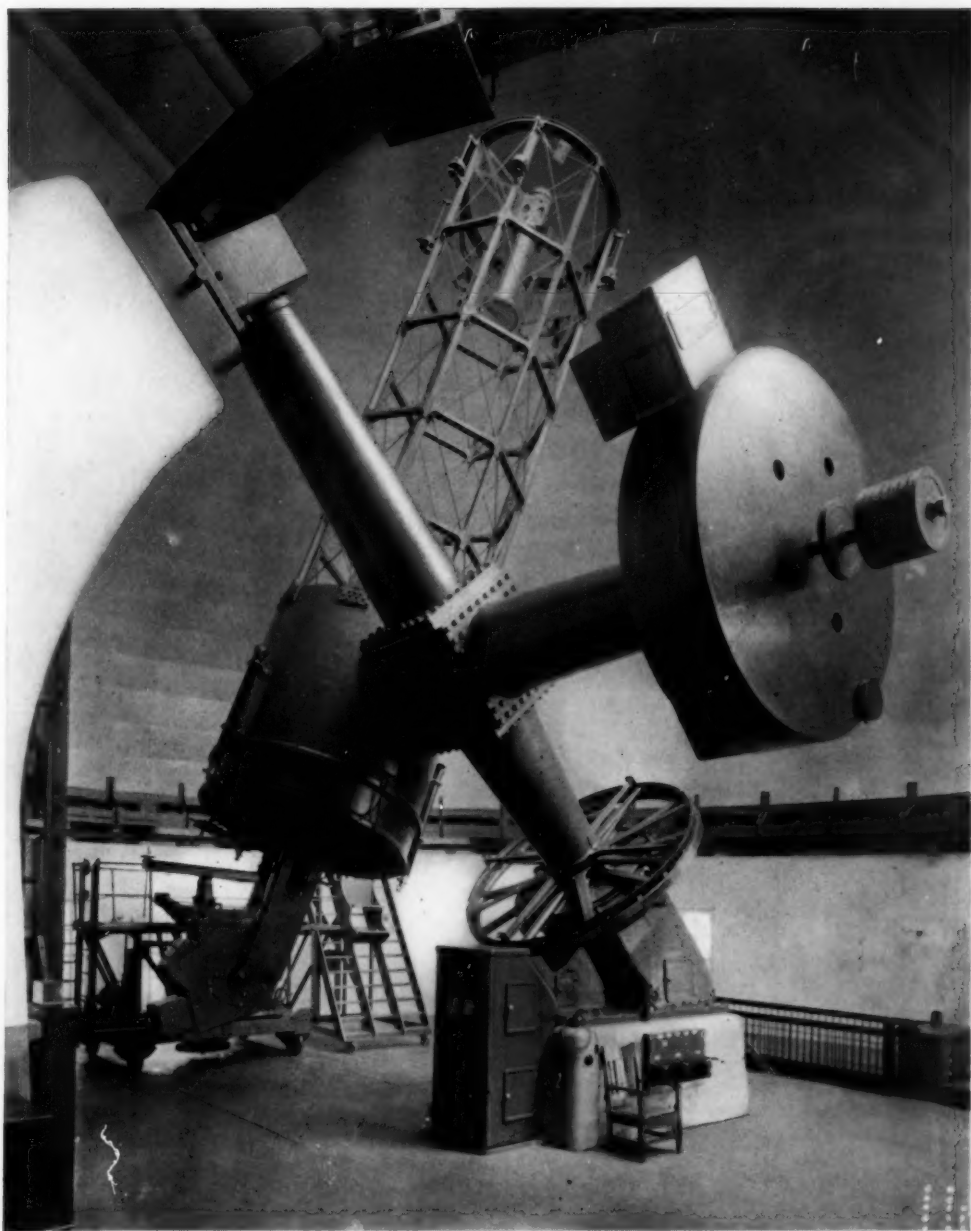
SEVENTY-TWO-INCH REFLECTING TELESCOPE WITH SPECTROGRAPH ATTACHED

the minute, a fine setting speed of 10′ to the minute, and a guiding speed of 30″ to the minute. The quick setting, clamping, and dome operating are performed at the more convenient of duplicate operating boards, one of which may be seen in Plate XII, on the east and west sides of the south pier. The fine setting and guiding are effected by means of a small portable board carried by the observer. There are no fine circles, but the coarse circles are graduated to single minutes of time in right ascension and to five minutes of arc in declination. The telescope can always be certainly set to within two minutes of arc of the catalogue position, and charting and uncertainty of identification for stars brighter than about the seventh magnitude are generally avoided. A further convenience is the fact that the settings in right ascensions are made on a large circle moving with the worm wheel, set to the sidereal time at the beginning of a night's work, and all mental arithmetic, liability to mistakes, and difficulty of setting to constantly changing hour angle are avoided.

In consequence of the perfection of the design and construction of this operating mechanism, the average time required to change from star to star, the time from the end of one spectrum exposure to the beginning of the next is only about three minutes and, if the stars are not far apart, is frequently only two minutes. Even though the moving parts weigh 45 tons, the telescope can be handled as easily and quickly as one of less than a fourth the aperture. In consequence of this, of the quality of the star images, and of the efficiency of the spectrograph, spectra can be accumulated rapidly, and the equipment has proved most efficient in this its principal work.

THE SPECTROGRAPH

As the stellar spectrograph to be described is in one sense a reversion to an early form, it will be of some interest to trace briefly the method of evolution. The universal spectroscope was probably the earliest type to be attached to a telescope and was probably chosen, as observing methods had not become standardized, because a choice of different dispersions and spectral regions would prove useful in experimental research. The best examples of

this type were those supplied by the Brashear Co. to the Allegheny, Yerkes, Lowell, Ottawa, and other observatories, which were undoubtedly beautiful instruments for general work but unsuited for the particular line of work—the determination of stellar radial velocities—into which stellar spectroscopy was soon narrowed. The adjustable features were not needed and were indeed a source of weakness in rendering the spectroscope more subject to differential flexure. Consequently the universal type was soon abandoned, and a rigid fixed form was developed, of which the Mills at Lick, the Bruce at Yerkes, and the Hartmann at Potsdam were all successful examples, and with which very accurate observations were obtained.

Both the universal and these later spectrographs had the drawback that the spectrograph proper and the truss which attached it to the telescope were one and the same construction, and the flexure, just as in a beam supported at one end, was a maximum. A great improvement in design, introduced by Campbell and Wright at the Lick Observatory, was to make the spectrograph proper self-contained in box form and attach it to the telescope by an external truss frame in which the spectrograph box was held flexibly at two suitably chosen supporting points. The flexure in such a form is evidently only about one-fourth that of the earlier types, and this form has been adopted in nearly all recent spectrographs.

In the spectrograph for the 72-inch telescope I have attempted to combine the advantages of the self-contained spectrograph box carried in an external attaching-frame by a two-point flexible support-system with the flexibility and general usefulness of a universal instrument. In more recent years the narrow field of radial-velocity observation of stars in the spectral region near $H\gamma$, with a three-prism spectrograph of linear dispersion about 10 A to the millimeter, has been broadened to include observations with one and two prisms, with various lengths of camera, and at various regions of the spectrum. No single spectrograph, indeed no two or three spectrographs, would be likely to meet the varied demands that might arise in spectroscopic investigation with such a powerful instrument as the 72-inch reflector. Hence, owing to the expense

that would have to be incurred for such a battery of spectrographs, it seemed wise to try to devise an instrument in which the change from one type to another could be made as quickly or even more quickly than spectrographs could be changed on the reflector, while any desired or used adjustment could be rapidly and certainly obtained. At the same time the spectrograph must be as rigid and as little subject to flexure as any of the fixed-form types.

These conditions have, I am convinced, been successfully met, and the methods employed will be developed as the description proceeds. The optical parts of the spectrograph were made by the Brashear Co. and give exquisite defining power, while the mechanical parts were made by the Warner & Swasey Co. The material, size, and form of the optical parts were determined by the writer, and the principles and general form of the mounting, of the minimum-deviation link-work, of the slit-head, comparison, and guiding apparatus, and of the constant-temperature arrangements were given to the Warner & Swasey Co. The latter is, however, responsible for the working out of the mechanical details, the form and material of the spectrograph box and attaching frame, and the style of construction and finish of the instrument. I need say no more than to state that in harmony of design and in character of workmanship and finish it is in keeping with the work on the telescope mounting, all of the very highest order.

THE OPTICAL PARTS

Practically all spectroscopists are agreed as to the advantage of a long collimator, the practical limit being the possibility of obtaining homogeneous material for the correspondingly large prisms. I had successfully used a prism of 51 mm (2 in.) aperture in the Ottawa single-prism spectrograph, and Adams has since used prisms of 63 mm (2.5 in.) aperture without difficulty. Hence it was decided to use prisms of the latter aperture, and, with the aperture-ratio of 1 to 18, this fixes the focal length at 114.3 cm (45 in.).

The most suitable material for the prisms was the subject of considerable experiment and calculation. I have previously said,[1]

[1] *Pub. Dom. Obs.*, Ottawa, **1**, 188.

"I have long been of the opinion that the dense flint, O 102, used in most recent spectrographs is too absorbing for the best results." This opinion has been borne out by experiments with a prism of baryta light flint and more recently by the results obtained with a prism of ordinary flint glass in the spectrograph here described. Measurements of the absorptions of various Jena glasses were obtained, and calculations of the losses due to reflection and absorption in prisms of 63 mm (2.5 in.) aperture of these

TABLE OF TRANSMISSION, DISPERSION, AND RESOLVING POWER
(Prisms of 63 mm aperture of various glasses)

Material Jena Numbers	Number of Prisms	Deviation at λ 4200	Angle of Prisms	Transmission of Prisms	Angular of Dispersion at Hγ	Linear Dispersion A per mm at Hγ Cameras of Focal Lengths			Resolving Power at at λ 4200
						381 mm	711 mm	965 mm	
U.V. 3248..........	1	48°31′	65 45	.822	5.24	103.3	55.3	40.8	16,160
Ultra-violet flint....	2	97 02	....	.703	10.48	51.6	27.7	20.4	32,320
	3	145 33	....	.615	15.72	34.4	18.4	13.6	48,480
	4	194 04	....	.556	20.96	25.8	13.8	10.2	64,640
O 722..........	1	51 41	64 15	.657	5.90	91.8	49.2	36.2	18,260
Baryta light flint....	2	103 22	....	.451	11.80	45.9	24.6	18.1	36,520
	3	155 03	....	.321	17.70	30.6	16.4	12.1	54,780
O 578..........	1	52 07	64 0	.636	7.12	76.0	40.7	30.0	22,220
Baryta flint........	2	104 14	....	.422	14.24	38.0	20.4	15.0	44,440
	3	156 21	....	.291	21.36	25.3	13.6	10.0	66,660
O 118..........	1	50 0	60 0	.768	8.51	63.6	34.1	25.1	....
Ordinary flint.......	1	54 40	63 0	.756	9.86	54.9	29.4	21.7	30,450
	2	109 30	....	.603	19.72	27.4	14.7	10.8	60,900
	3	164 00	....	.503	29.58	18.3	9.8	7.2	91,350
O 102..........	1	60 0	64 0	.467	12.89	42.0	22.5	16.6	52,700
Dense flint........	2	120 0	....	.235	25.78	21.0	11.2	8.3	105,400
	3	180 0	....	.126	38.67	14.0	7.5	5.5	158,100

NOTE.—It is evident, from a comparison of dispersion, resolving power, and transmission, that, with slit-widths giving the same purity of spectrum, the ultra-violet flint and the ordinary flint are much superior to the others and approximately equal themselves. The greater dispersion given by the ordinary flint, the higher resolving power obtainable, its lower cost, and the greater likelihood, owing to its being produced in large quantities, of homogeneity, led to its choice.

glasses and of their relative efficiencies for given dispersion and resolving power as given in the accompanying table, showed that one of the ordinary flints, O 118 of the Jena works, a glass very generally used for the flint component of telescope objectives, gave the most favorable showing. Schlesinger's measures of the absorption of the flint element of the 30-inch Allegheny objective, made of O 118 glass, confirmed these calculations, and, as this type is made in large quantities and is more likely to be homogeneous

than some of the less-used varieties, I had no hesitation in choosing it for the prisms of the spectrograph. Material for the three prisms was ordered from Jena by the Brashear Co. in August, 1914, but of course could not be supplied, owing to the war. Until these or some similar prisms are available, we are fortunate in being able to use a 60° prism of the same aperture and the same material made by the Hilger Co. for a Littrow spectrograph for Toronto University and kindly lent temporarily to me by Professor Chant. Use of this prism has shown it to be of excellent quality and of remarkable transparency in the violet, considering its density and dispersing power. Although its dispersion is only about 25 per cent less than O 102, its absorption at λ 4000 is certainly less than half, and in spectra of Nova Aquilae measures of 19 displaced hydrogen lines, extending to λ 3655, were made.

Owing to this transparency in the violet of the prism and to the absence of absorbing material in the telescope objective, the central ray could be advantageously placed considerably farther to the violet than has been usual hitherto. The position chosen was at λ 4200 in order to take advantage of the larger number of lines in early-type stars around this region than to the red of λ 4500. However, the adjustable feature of the spectrograph will readily admit of shifting the camera and prisms in a few moments, so that any other region is central, and any part of the photographic spectrum can be reached with the same objectives without the color-curve becoming unmanageably steep.

The collimator and the two camera objectives supplied are all of the Hastings-Brashear triplet type, and as the former is 63 mm and the latter 76 mm aperture the use of Canada balsam as a cementing agent was not deemed allowable on account of the strain almost certain to be introduced. However, as the internal reflections in such triplets when uncemented cause a loss of about 20 per cent in each, these objectives had at my suggestion a film of watch oil placed between the components, which has acted perfectly and shown no signs of deteriorating or drying out after a year's use. The aperture of the collimator objective is 63.5 mm (2.5 in.) and its focal length 1143 mm (45 in.). The apertures of the camera objectives are 76.2 mm (3 in.), and their focal lengths are 711 mm

(28 in.) and 965 mm (38 in.) respectively. These objectives and the prism are so well corrected that the spectra given by the instrument are of exquisite definition and leave nothing to be desired. A third camera objective of the Cooke triplet type of 76 mm aperture and 380 mm focus, ordered from the Brashear Co., has not yet been received.

The linear dispersions of the spectrograph with these three cameras and with the one, two, and three prisms destined for the instrument, and also with the 60° prism now in use, are given in the table on p. 214.

SLIT AND ACCESSORIES

The slit-jaws are of polished nickel inclined at an angle of $3°5$ to the normal to the optical axis. One of the jaws is fixed, and the other is separated from it by a micrometer screw reading to thousandths of an inch. The guiding is effected in the usual way by the star's light reflected from the jaws into a right-angled reflecting prism at the end of a broken guiding telescope. The bend of $45°$ allows the guiding ocular to be rotated into the most convenient observing position.

The method of applying star and comparison spectrum is new, offers some advantages over other devices, and hence merits a more detailed description. Directly above, and with their edges parallel to the slit, are two small right-angled reflecting prisms, one for each set of comparison lines, which reflect the comparison light from its original direction, perpendicular both to the slit and the optical axis, down through the slit. These prisms can be brought into contact or separated symmetrically along the direction of the slit, so as to change the distance apart of the comparison spectra, by means of a right-and-left screw, and can also be moved, transversely to the slit, toward or from the comparison source, by rack and pinion. The prisms are held in their cells by thin metal plates shaped like the diagram, Fig. 1, which just clear the slit-jaws and serve as limiting diaphragms for star and comparison light. The star's light passes through the wedge-shaped opening a, and the comparison light through the rectangular openings b, b. The wedge-shaped opening will give any width of spectrum between o

and o.8 mm, depending upon its position when the prisms are in contact, a notch being cut, as shown, in the front of each above the wedge to allow the light unobstructed passage. Three adjustable abutting screws, against which the rack and pinion can move the prisms, allow the usual widths to be reproduced at will. At the same time the rectangular openings give comparison spectra of the same length and separation, whatever the width of star spectrum within the preceding limits. If nebular or planetary spectra are desired, all that is necessary is to separate the prisms by the right-and-left-hand screw the required distance, and the comparison
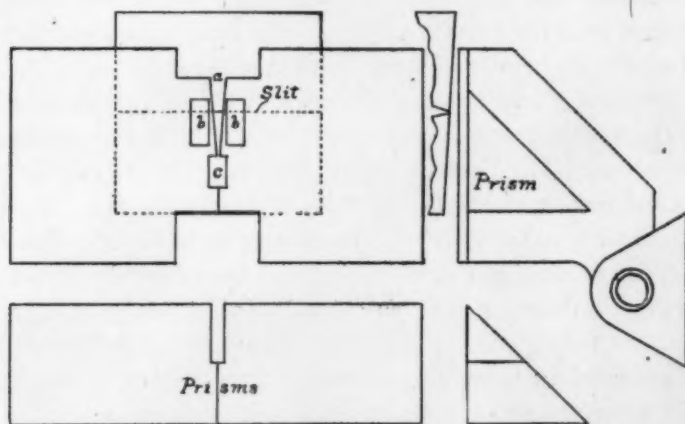
Fig. 1.—Slit diaphragm and comparison prisms, 1.7 times natural size

spectra remain automatically at the same separation from the edges of this widened spectrum. The rectangular notches *c* are for the purpose of placing a central strip of comparison spectrum between the outer strips, which, in conjunction with a semicircular diaphragm inserted at the collimator objective, enables the Hartmann method of focusing the camera to be readily applied.

Evidently the comparison spectrum can be applied as often as desired without stopping or affecting the exposure on the star spectrum or touching the slit-head. All that is necessary is to snap on the switch that starts the iron arc used as comparison source, which is fed by the 220-volt direct current used in operating the telescope. This device works admirably, gives exactly similar

and uniformly exposed comparison spectra, always remains in adjustment, and has the additional advantage over previous devices of readily giving adjacent comparison spectra for determining camera focus by the Hartmann method. Both arc and guiding telescope are adjustably attached to the supporting frame, do not touch spectrograph box or slit-head, and no pressure on them can possibly affect the position of the lines.

<div align="center">THE SPECTROGRAPH BOX</div>

As previously stated, the box carrying all the optical parts is a self-contained unit and is carried and supported without stress in collimation with the telescope by a surrounding frame, to which it is attached at two points. The general shape of this box, which is a single aluminum casting, is well shown in Plate XIII, which illustrates the spectrograph proper in its supporting frame attached to the telescope. The circular opening in the side directly over the prisms and link-work enables them to be readily reached for changes and is normally covered by the three plates on the floor. The three projections to the right are for inserting the cameras for use with one, two, or three prisms. Another projection for carrying the collimator tube extends centrally up within the supporting frame, and this is united to the third camera projection by a box girder, seen in the photograph, cast integral with the spectrograph box. This box, as it is in one casting with only the circular opening at one side, is exceedingly stiff and, being of aluminum, comparatively light.

The minimum-deviation link-work, which carries and maintains prism cells and prisms always at minimum deviation, whatever part of the spectrum is central, is similar in design to that used by the Brashear Co. in their universal spectroscopes, with the addition of guiding links to always align the cameras, when used with one, two, or three prisms, along the optical axes. It is exceptionally well made, without lost motion or backlash of any kind; and one can be certain that after the prisms are adjusted in their cells they are always at minimum deviation and the axes of the cameras parallel to the central emergent ray, whether one, two, or three prisms are used, and whatever the region of the spectrum. A scale

PLATE XIII
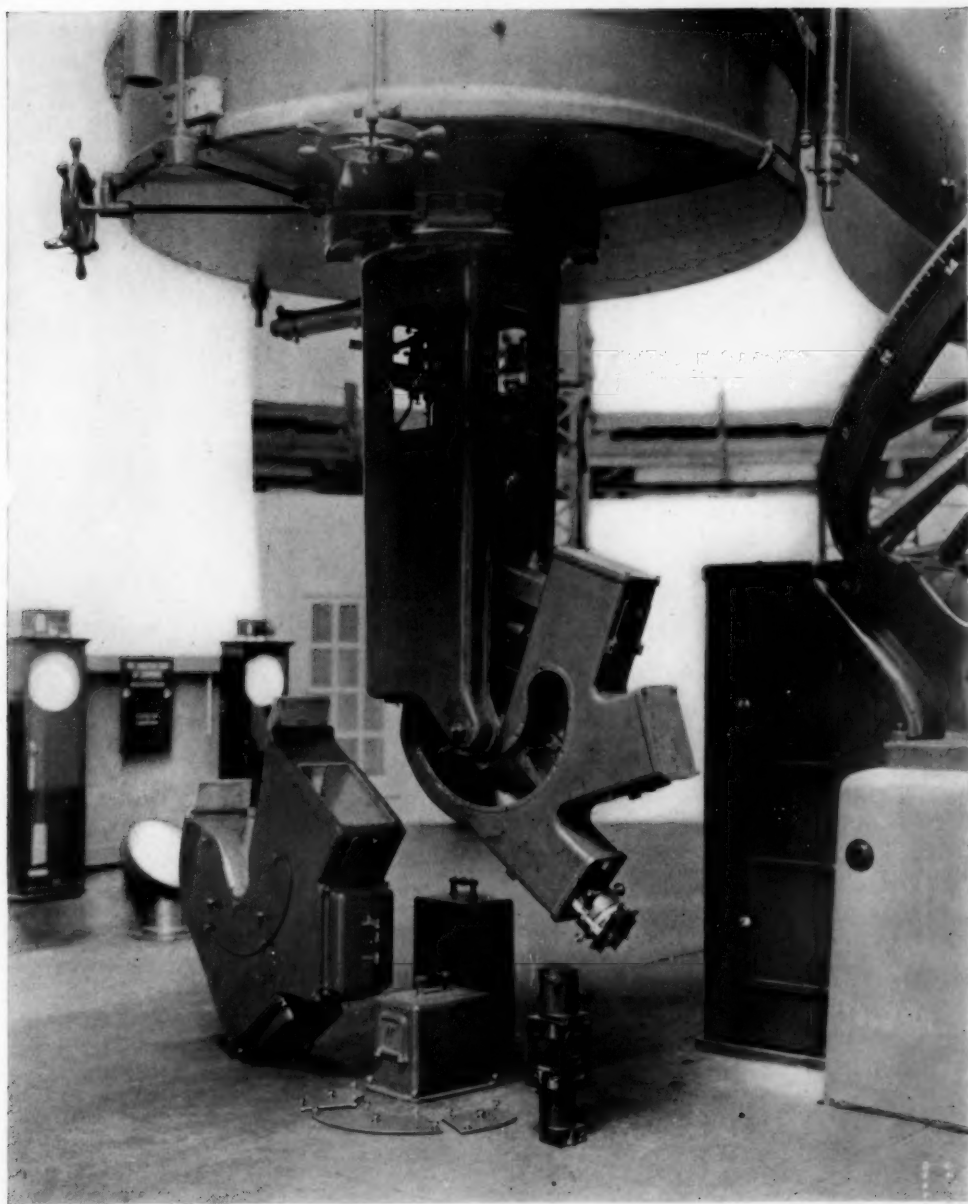
SPECTROGRAPH WITH TEMPERATURE CASE DETACHED

and magnifying index enables any region to be accurately set to or recovered when desired. This link-work, however, is not depended on for rigidly holding prisms and camera in position but only serves to fix their relative positions. Bolts through each corner of the triangular-shaped prism tables, and two at each end of the cameras, passing through slotted holes in the 16-mm thick base of the box, enable prisms and camera, when adjusted by the link-work, to be as rigidly fixed to the spectrograph box as if it had no adjustable features whatever, or was specially made for one dispersion and wave-length only. The prisms are held in substantial cast-iron cells, these latter being attached to the movable prism tables by screws and dowel pins, so that if, for example, the second prism has to be removed to use the one-prism form, this is done by unscrewing four screws and taking out cell and prism as a unit. The dowel pins insure its return to exactly the same position and adjustment.

The collimator tube is of steel, and the cameras are of brass. Previous experience has shown that with the triplet type of objectives such construction made change of focus with change of temperature compensatory, and no change of camera setting is necessary between winter and summer temperatures, which is a great convenience. The collimator tube is placed in the most convenient position and firmly clamped there, as the focusing of the star image on the slit is effected by moving the secondary mirror in and out with a slow motion operated by a hand wheel near the guiding eyepiece. This method is very accurate, sensitive, and convenient, and the focus can be readily and closely determined visually by the appearance of the image on the slit-jaws.

The medium-focus camera is in position for using one prism, in the photograph of the spectrograph, Plate XIII, while the short-focus camera is on the floor. They are of exceptionally rigid construction to avoid flexure; the objectives are permanently screwed in the inner ends of the tubes, while focusing is effected by rack and pinion on the plate-holder end, read by scale and vernier to tenths of millimeters. The plate-holders are of metal, book-form style, opening in the middle, the plate 2×4 in. in size being held down by a spring against a raised surface on the edge of an opening 1 by 35 in. in the

front half of the holder.   The plates are hence supported parallel
to the spectrum all along its length, only half an inch away from
it, and any curvature of the plate will hence have negligible influ-
ence on the focus or measures.   The plate-holder and carrier move
transversely in ways so that, if desired, several spectra may be made
adjacent to one another on the same plate.   In addition a tilt of
about 15° each way can be given to the plate to enable it to be
adjusted tangent to the focal plane.   The medium- and long-focus
cameras can be operated through doors in the temperature case,
but, as the plate comes within the spectrograph box in the short-
focus camera, suitable openings covered by hinged doors are
made in the camera projections of the box and corresponding open-
ings in the temperature case to enable the plate-holders to be
inserted and changed.

THE SUPPORTING FRAME

This, as well as the spectrograph box, is of cast aluminum, both
being exceptionally fine castings.   It is of hollow, rectangular,
prism-shaped form, with a substantial circular flange at the top,
which is held by 8 cap screws firmly to the revolving cast-iron ring
at the lower end of the tube.   The spectrograph box is held in the
frame by two shafts, of which the lower one, which can be seen in
the figure, Plate XIII, at the bottom of the frame, forms the princi-
pal support.   The upper shaft is within the small circular cover plate
on the side of the frame and serves to keep the instrument from
rotating on the lower shaft.   Both of these shafts are so attached
to the frame and pivoted in the box that no possible flexure of the
former can produce any stress in the latter, which is carried, as it
were, in a flexible cradle.   Collimation of the spectrograph with
the optical axis of the telescope is effected by adjustments on these
two shafts.   This collimation was performed before the optical
parts were placed in the spectrograph by turning the telescope
tube vertical and hanging a steel plumb line down its exact center
and through the collimator tube.   The spectrograph box was then
adjusted on the two shafts until the wire was exactly central at the
upper and lower ends of the collimator tube.   Flexure in other posi-
tions of the telescope will change the collimation slightly, but this

will be of the second order, unavoidable, and cannot cause appreciable error in the observations. The inside of the frame where it surrounds the collimator projection and tube is lined with felt, has part of the heating wires on the two sides, and really forms part of the temperature case.

THE TEMPERATURE CASE

The temperature case is attached to, and indeed forms a part of, the supporting frame and does not touch the spectrograph box at any point. The very workmanlike and convenient combination of box, frame, and case, due to the Warner & Swasey Co., forms a new type of design of simple arrangement and fine proportions, and one in which the necessary adjustments or changes can be made with the greatest convenience. The temperature case proper can be seen detached in Plate XIII and attached in Plate XII. It has sheet-aluminum sides and cast-aluminum edges, is firmly screwed to the supporting frame, and is lined throughout, and the entire spectrograph box is hence inclosed with felt one-half inch thick, forming a very efficient heat insulation. Large circular openings at each side and covers for the cameras, all quickly detachable, enable any changes of adjustment to be made without removing the case, while plate-holders are changed through hinged doors.

The inside of the case is heated by passing the 110-volt lighting current through wires uniformly distributed over and sewed to the felt, and, as the difference between inside and outside temperatures is generally not more than three or four degrees Centigrade and the case is well heat-insulated, very little current is required. Exploring thermometers have shown very nearly uniform temperature all over the inside of the case, even when the air-stirring fan within is not operating. The heating current is turned on and off automatically by a mercury-contact thermometer operating a relay, and this works satisfactorily, there rarely being a change greater than $0°1$ C. during a night's work. It is proposed, as soon as it can be obtained, to instal a Callendar recorder to regulate and record the temperature within the case. As the regulating resistance can be divided between the inside of the case and the inside of

the prism box, it should be possible by suitably proportioning the amount of resistance in each to keep the spectrograph constant to within 0°.01 C.

PERFORMANCE OF THE SPECTROGRAPH

The collimator focus was adjusted by Schuster's method, and the camera is focused by the Hartmann method, the very convenient means for applying this test having already been described. The field of the medium-focus camera, focal length 711 mm, which is the one now in use, is slightly convex toward the lens, the deviation at λ 4600 at one end and at λ 3900 at the other from the tangent plane at λ 4200 being less than 0.1 mm. Evidently, when the dispersion is greater, with two prisms, say, the field will probably be practically flat. As it is, by accommodating the focus slightly, no part of the spectrum between λ 3900 and λ 4600 will be out of focus to a greater extent than 0.05 mm, too small, when even only approximately uniform illumination by star and spark light is secured, possibly to affect the measures. As previously stated, no change of camera setting with change of temperature is required, but as a precaution the setting is periodically tested.

Tests for flexure with the extended one-prism form, where it would be the maximum, showed quite inappreciable displacements, even under the most unfavorable conditions and abnormal hour-angle changes.

However, the best test of the performance of the spectrograph is actually making and measuring spectrograms, and under this final exacting test the instrument has exceeded expectations. It has only been used with the single prism and medium-focus camera giving a linear dispersion at Hγ of about 35 A to the millimeter. About 1300 spectra of stars, mostly fainter than 6.0 photographic magnitude, have been obtained, and half of them measured. Under average conditions of seeing and of the silver surfaces, a well-exposed spectrum of a star of photographic magnitude 7.0 can be obtained in twenty to twenty-five minutes. I am convinced that with a good silver coat and good seeing this could easily be reduced to fifteen minutes.

The accuracy of the resulting spectrograms is also very gratifying. It is generally considered that a three-prism spectrograph

should give radial velocities with a probable error of half a kilometer. It would naturally be expected that with a dispersion less than one-third the probable error would be trebled, but this is by no means the case. The resulting probable error for stars with good lines, F to M types, is well under 1 km, and for G, K, and M types seems to average about ± 0.85 km per second. On stars with few or poor lines this will of course be increased, but if the lines are poor better values can probably be obtained with low than with high dispersion.

In view of the accuracy obtainable with this dispersion, and in consideration of the fact that three-prism spectra require at least five times the exposure, it seems to me questionable, for radial velocities of stars fainter than sixth magnitude, whether the doubled accuracy of determination justifies the additional time consumed at the telescope. Some special tests have shown that as far as can be determined the systematic displacements are negligible in comparison with the errors of measurement of the spectra, and that by remeasurement the range in values and the probable errors are generally reduced. Double the number of single-prism plates could be obtained in 40 per cent of the time of three-prism plates, and, with care in the measurement, the mean values should not greatly differ in accuracy in the two cases.

The test of actual use has convincingly shown that both telescope and spectrograph are most efficient and convenient to operate, and we have not been able yet to discover any features that could be improved. A great part of this success is undoubtedly due to the ever-present determination of the makers, of both optical and mechanical parts, to produce the best possible instrument regardless of cost, and it is only my duty as well as my pleasure to express here my gratitude to the John A. Brashear Co., Ltd., and the Warner & Swasey Co., for the spirit with which they attacked the various problems that arose, and for the success that attended their efforts to make an equipment for astronomical research capable, by its accuracy and efficiency as well as by its size, of so .greatly extending our knowledge of the universe.

A FURTHER STUDY OF METALLIC SPECTRA PRODUCED IN HIGH VACUA[1]

By EDNA CARTER and ARTHUR S. KING

Using the methods employed in a former investigation,[2] we have made a study of the spectra of manganese, titanium, magnesium, and cadmium, as produced by vaporizing the substance through the heating effect of a stream of cathode rays and exciting the vapor to luminescence by the bombardment of the cathode particles. The spectra thus obtained seem to be quite definite and characteristic of this mode of excitation. Additional observations of the calcium spectrum have confirmed the previous results, and for the iron spectrum a considerable number of lines has been obtained with a slightly different arrangement of circuit.

The form of the discharge-chamber is similar to that used in the previous work. In order to withstand the heat developed by the heavier discharge required to vaporize the more refractory metals, the parts formerly of glass were replaced by fused quartz or silica-ware. The glass bell-jar was superseded by an inverted crucible of silica-ware eight inches in diameter. Through the top a hole was bored into which a tube, T, Fig. 1, of opaque quartz was fitted by tapering it slightly at the end. Through this was passed another similar tube, which was fitted into a hole bored into a small quartz crucible, B, about two inches in maximum diameter. This flared around the cathode, C, and helped to concentrate the discharge. The aluminum cathode was melted by the heat, so it was replaced by a more massive one of copper faced with iron. This was connected by a copper rod with a copper receptacle, E, in which ice was placed. The joints were cemented with sealing-wax. In the large crucible two holes were bored opposite each other, into which tubes bearing quartz windows were set for viewing and photographing the luminescence spectrum just above the anticathode.

The base-plate of $\frac{3}{4}$-inch glass was retained, protected from the heat by a $\frac{1}{4}$-inch aluminium plate, *D*, supported a short distance above it. An opening in the aluminum plate, covered by a quartz window, permitted a view of the discharge from below. The anode, *A*, was introduced through a quartz tube, which projected through the base-plate and the aluminum plate. The metal to be examined, *M*, was contained in a quartz tube supported in a base-plate, *F*, of the same material. The tube was slotted vertically at the upper end to expose the luminescent vapor, while also confining it. The metal was placed just below the slot, the quantity used depending upon the ease with which it could be vaporized.

The discharge was produced by a transformer with a rotary spark-rectifier. The evacuation was effected by two rotary oil pumps in series. In general, the metal, as soon as it began to vaporize, aided the evacuation by absorbing the gases in the chamber. Sometimes the absorption was so complete that it was necessary to leave a fine capillary tube open to the outside air in order to keep up the discharge. The iron vapor did not seem to have this absorbing power, so that it was difficult to obtain a satisfactory spectrogram of iron except by making the metal the anode. When a Fe-Mn alloy was used there was no trace of iron in the spectrum of manganese thus obtained, although a hole several millimeters deep was made in the metal at the focus of the rays.
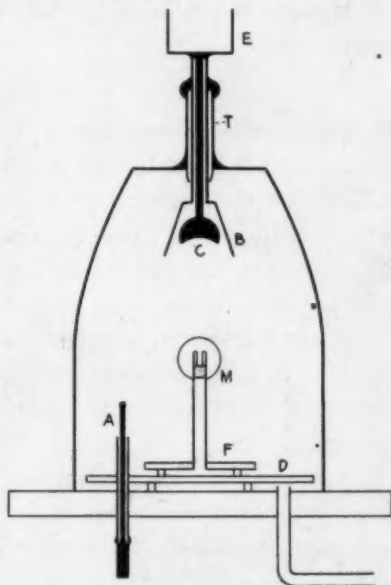
Fig. 1

The spectra were photographed for the most part in the first order of a 1-meter concave grating, the scale being 1 mm = 17 A. In order to detect any differences in the spectrum at different

distances from the hot metal, photographs of the spectra of titanium, magnesium, and calcium were also made with a quartz spectrograph, but no notable difference was found. The exposure time varied from fifteen minutes in the case of cadmium, with a discharge current of about 5 milliamperes and a parallel spark of 20–30 mm, to seventy minutes for titanium, the current being 9–12 milliamperes and the parallel spark 60–120 mm in length. It was imprudent to run this latter discharge more than ten minutes at a time on account of the warming of the sealing-wax joints.

MANGANESE

The number of manganese lines identified is the largest thus far photographed in luminescence spectra. The best spectrogram was obtained with a current of 8 milliamperes, the parallel spark-gap being about 5 cm. The lines which appear in the luminescence spectrum are listed in Table I, with their intensities in this source and for the furnace (at about 2200° C), arc, and spark. The intensities for the arc and spark are taken from the tables of Exner and Haschek, and, while on a different scale from the other estimates, they serve to show in which of these two sources a line is relatively strong.

A comparison of the luminescence lines with those of the three other sources serves to show the distinctive character of the luminescence emission. Among the lines relatively strong in the spark, only λ 4235 is notably strong in the luminescence. Of a group of nine enhanced lines from λ 3442 to λ 3498 only a trace of the strongest appears.

An inspection of Table I shows also many divergences of the luminescence spectrum from that of the furnace. A notable contrast is given by the moderately strong luminescence lines λλ 4058, 4060, and 4062, which do not appear in the furnace. The resemblance to the arc spectrum is closer, but this is found to result from the fact that the luminescence emission picks out certain arc lines and gives them with high intensity. That most of the luminescence lines appear also in the furnace is a consequence of the usual condition that most of the arc lines are given with greater or less intensity by the furnace.

TABLE I

MANGANESE

λ (Exner and Haschek)	Luminescence	Furnace	Arc	Spark	λ (Exner and Haschek)	Luminescence	Furnace	Arc	Spark
2576.20	6	....	4R	30R	3320.82	4	4	2	1
2593.82	5	....	4R	15R	3330.80	4	6	2	....
2605.78	3	....	4	10R	3442.13	1		2	30
2704.00	2	....	5	....	3532.02		10		2
2713.42	2	....	5	....	3532.15	30	15	20	3
2726.22	2	....	5	....	3532.26		15		3
2761.03	3	....	3	3	3547.93		15	10	4
2776.25	1	....	2	....	3548.16	40	15	10	3
2778.68	1	....	2	....	3548.30		10	3	3
2782.85	1		2		3569.65		20	15	5
2794.92	150	200R	50R	5R	3569.96	40	15	10	4
2798.37	125	150R	50R	5R	3570.23		12	4	3
2799.99	1	2	2	1	3576.25	5n	....	1	....
2801.20	100	100R	50R	5R	3577.99	20	15	10	5
2802.90	1	1	2	1	3580.3	4n		1	....
2818.09	1	3	3	1	3586.69	12	10	5	4
2858.85	1	1	2		3595.29	3	7	4	2
2872.68	1	1	2	....	3607.69	6	10	5	3
2914.71	3	5	8	1	3608.66	8	10	5	3
2925.67	5	10	8	1	3610.49	5	8	5	3
2930.35	1	1	2		3619.42	5	6	4	3
2933.19	2	1	3	15	3623.96	3	6	4	2
2939.40	3	1	3	20	3629.89	1	4	3	1
2940.50	6	4	8	1	3790.38	1	6	3	4
2949.31	5	1	3	30	3800.70	1	....	2	2
3044.69	25	5	5	2	3806.90	15	12	10	8
3054.53	8	8	4	2	3809.75	2	8	5	6
3062.30	4	5	4	1	3823.64	10	10	5	6
3066.19	5	5	4	1	3824.03	1	6	4	4
3070.46	6	5	4	1	3829.80	3	3	3	3
3073.33	5	5	4	1	3834.01	2	6	4	4
3079.80	3	5	3	1	3834.50	7	10	8	8
3081.52	1	4	3	1	3839.90	1	5	4	5
3148.36	3	5	3	1	3841.23	3	7	5	6
3161.19	4	6	3	1	3844.12	1	5	3	4
3178.61	5	7	3	1	3926.63	2	....	3	4
3212.98	1	10	2	2	3943.05	1	....	2	2
3217.04	10	30R	1	1	3982.73	1	5	2	3
3224.00	25	30R	•2	1	3985.40	1	1	2	3
3228.20	15	20r	3	3	3986.98		1		4
3230.81	2	8	2	2	3987.26	4	1	2	4
3234.0	2	1	2	....	4018.28	3	20	10	8
3235.1	3n	1	2	....	4030.92	150	200R	100R	20R
3236.90	8	8	2	3	4033.21	100	150R	100R	20R
3237.4	4	3	2	....	4034.62	100	150R	100R	10R
3240.53	1	10	2	1	4035.88	1	15	5	8
3240.75	1	7	2	1	4041.53	10	40	20	10
3243.93	3	6	3	2	4048.90	3	15	8	8
3247.80	1	....	1	....	4055.70	4	20	4	8
3248.64	6	6	3	3	4058.10	6	....	3	2
3253.09	2	7	3	2	4059.54	8		3	2
3254.14	1	3	2	1	4061.90	10	....	4	3
3256.25	3	6	3	2	4063.70	1	20	5	6
3258.52	2	6	3	2	4079.38		10		5
3260.40	1	6	3	2	4079.61	3	10	3	5
3264.83	4	8	3	2	4083.11	2	10	4	6
3278.65	1	4	2	1	4083.82	2	12	3	6
3280.90	3	4	2	1	4147.71	1		2	2
3297.01	2	4	2	1	4235.41	10	4	10	20
3312.05	3	2	2	....	4239.00	1	1	3	5
3313.41	5	1	2	....	4257.83	1	1	3	4
3313.70	5	1	2	....	4266.10	2	1	3	5
3314.59	5	2	2	....	4281.30	2	2	3	5
3315.07	8	2	2	....	4436.52	1	1	8	5
3316.61	4	1	1	....	4451.78	•2	8	8	10
3317.47	20	4	3	1					

TABLE I—*Continued*

λ (Exner and Haschek)	Luminescence	Furnace	Arc	Spark	λ (Exner and Haschek)	Luminescence	Furnace	Arc	Spark
4455.20 } 4455.51	15	2	{ 5 5	3 3	4766.63....	1	6	8	3
4456.02.....	5	1	5	3	4783.62....	15	50	30	8
4457.76.....	8 (	1	5	4	4823.71....	15	50	30	10
4458.48.....	15	2	6	5	5341.25....	15	50	15	8
4461.30.....	8	1	5	4	5394.89....	1	40	8	1
4462.20.....	40	3	10	8	5420.61....	6	25	10	3
4464.88.....	1	4	8	5	5470.88....	5	15	10	2
4754.24.....	10	50	30	8	5481.61....	2	8	8	1
4762.60.....	2	10	10	4	5517.00....	2	10	10	2
4766.08.....	1	4	6	3	5537.99....	2	6	10	1

Two sections of the manganese luminescence spectrum, with that of the arc for comparison, are reproduced in Plate XIV. While many of the luminescence lines are too faint to appear in the copy, the general effect of certain arc lines being brought out while other strong ones are absent may be clearly seen.

TITANIUM

The titanium luminescence lines are given in Table II, with the arc and spark intensities of Exner and Haschek for comparison. The results, considering the high melting-point of this element, show the possibility of studying the more refractory substances by this method. It will perhaps be sufficient to note briefly the points of difference from the furnace, vacuum arc, and the arc and spark in air, photographs of which were available for comparison. As for manganese, a decided selective action by the luminescence is apparent, many strong arc lines being absent or very faint. A comparison with the furnace spectrum, however, shows many resemblances. The prominent luminescence lines are strong also in the furnace and reverse at high temperature, their relative strength in a given region often being not greatly different in the two sources. There are exceptions, however, to this rule, and strong furnace lines are frequently lacking in the luminescence spectrum. There is an absence of even a slight approach to the spark spectrum, since the enhanced lines of titanium, many of which appear with considerable strength in the arc and can be obtained faintly even in the furnace, are either absent in the luminescence or among the fainter lines of this spectrum. The

PLATE XIV
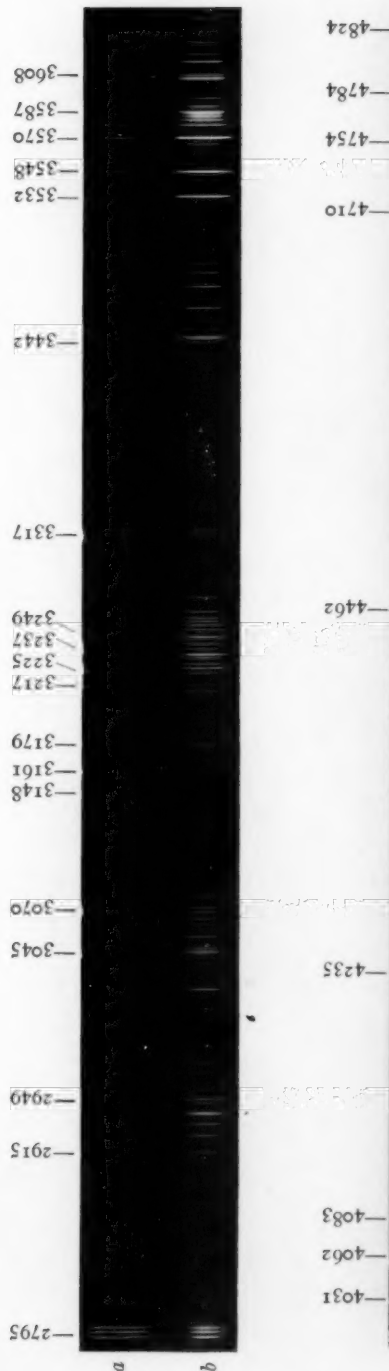
(a) Luminescence and (b) arc spectra of manganese

TABLE II
TITANIUM

λ (Exner and Haschek)	Luminescence	Arc	Spark	λ (Exner and Haschek)	Luminescence	Arc	Spark
2641.20	1	2	2	3753.77	3	3	3
2644.35	1	2	3	3759.48	1	10	20
2646.71	1	2	2	3761.50	1	10	10
2942.12	4	3	4	3771.84	10	4	3
2948.37	4	3	2	3786.20	1	3	3
2956.27	4	2	2	3789.43	tr	2	2
2983.41	tr	2	2	3796.02	tr	2	2
3000.99	1	2	2	3798.44	tr	2	2
3186.58	10	8	3	3818.35	tr	2	1
3192.14	12	8	1	3836.90	1	2	......
3200.08	20	8	3	3846.54	1	2	2
3203.55	1	2	2	3921.61	2	5	2
3214.38	1	2	1	3924.71	10	8	3
3234.68	1	8	15R	3930.04	8	8	3
3236.72	1	5	6R	3947.98	10	10	3
3342.01 } 3342.30	50	{4} {3}	10R	3948.87	40	12	4
3349.17 } 3349.56	6	{3} {8}	8R 10R	3956.50	40	15	4
3354.80	60	8	3	3958.39	60	15	5
3358.56	1	2	......	3963.05	6	8	3
3361.41	8	10	30R	3964.48	6	8	3
3370.61	40	5	2	3981.95	50	15	3
3371.62	70	10	2	3982.63	2	8	3
3373.03	1	3	20R	3989.94	60	10	6
3377.70	15	10	3	3998.80	70	20	6
3379.35	10	3	1	4009.12	15	8	4
3382.47	3	3	1	4024.76	20	10	3
3383.90	3	3	20R	4078.62	1	8	4
3385.80 } 3386.10	20	{2} {5}	....	4112.87	6	5	2
3390.84	tr	2	2	4122.30	1	3	2
3394.74	tr	2	10	4123.70	1	3	2
3444.49	tr	4	10	4127.67	2	3	3
3505.06	1	3	30	4137.46	tr	3	2
3610.35	1	4	2	4151.12	1	3	3
3635.61	50	15	3	4171.20	tr	3	2
3642.81	70	15	3	4200.90	tr	2	2
3653.66	100	15	4	4282.87	2	5	3
3654.74	2	3	2	4286.19	1	10	4
3658.26	12	4	3	4289.26	1	15	4
3660.80	2	3	2	4291.19	1	10	2
3669.15	3	3	2	4295.93	1	10	4
3671.85	10	4	3	4298.89	1	12	4
3685.37	2	8	100	4300.73	4	15	2
3690.09	2	3	2	4301.24	5	15	3
3717.52	5	5	2	4306.09	6	20	8
3722.73	7	3	3	4314.96	10	5	3
3729.97	50	8	4	4318.85	1	10	3
3741.25	70	15	2	4321.89	tr	8	3
3748.22	1	2	6	4325.36	tr	8	3
3753.00	100	15	5	4326.54	tr	4	2
				4427.28	tr	10	4
				4430.52	tr	3	2
				4434.16	tr	5	3

TABLE II—*Continued*

λ (Exner and Haschek)	Luminescence	Arc	Spark	λ (Exner and Haschek)	Luminescence	Arc	Spark
4449.35	1	10	5	4599.40	tr	3	1
4451.13	1	8	3	4617.40	tr	10	8
4453.52	12	8	3	4656.63	25	8	3
4455.50	12	12	4	4667.77	25	10	5
4457.61	15	15	5	4682.10	30	10	6
4496.35	tr	10	3	4981.93	6	20	10
4512.90	1	15	4	4991.24	5	20	10
4518.19	2	15	4	4999.68	4	20	10
4522.98	2	15	4	5007.35	2	20	10
4527.47	1	15	4	5014.39	8	20	8
4533.40	20	20	5	5036.08 }	2	{ 10	8
4534.95	10	15	4	5036.65 }		{ 10	8
4535.71 }	40	{ 8	3	5038.59	1	10	8
4536.12 }		{ 10	2	5040.14	3	10	3
4536.25 }		{ 10	2	5064.79	3	10	5
4544.88	1	10	3	5173.92	1	15	5
4548.93	1	8	3	5193.12	1	20	8
4552.70	1	10	4	5210.59	2	20	10
4555.70	1	10	3				

titanium vacuum arc also does not show differences from the ordinary arc in the direction of a resemblance to the luminescence spectrum. The effects point to a distinctive character in the emission resulting from the cathode bombardment.

MAGNESIUM

Magnesium metal was used as the anticathode, and spectra were obtained both for the usual arrangement with an insulated target and when it was connected as anode. The intensities of the lines under these conditions are given in Table III. The difference found was chiefly in the general intensity of the light, the anode connection giving a much stronger spectrum when the same length of parallel spark was used.

An interesting mixture of arc and spark lines is presented by these high-vacuum spectra. Six ultra-violet enhanced lines, λλ 2791, 2796, 2798, 2803, 2929, and 2937, are strong for both arrangements of the anticathode. These are placed by Fowler[1] in a series of "wide doublets." The much-studied enhanced line λ 4481, belonging to a different series, is just visible in the lumi-

[1] *Philosophical Transactions of the Royal Society*, A, **214**, 225, 1914.

nescence spectrum, and in the anode spectrum is much weaker than the adjacent arc lines. The ultra-violet doublets appear in the ordinary arc in air, while λ 4481 does not. It appears that in the high-vacuum spectra for magnesium we have a slight approach to the spark spectrum, but not as pronounced as can be obtained in the

TABLE III

MAGNESIUM

λ (Exner and Haschek)	Lumi-nescence	Anticathode as Anode	λ (Exner and Haschek)	Lumi-nescence	Anticathode as Anode
2630.52		1	2936.99	15	30
2633.13		2	2938.67	4	8
2646.61		tr	2942.21	6	15
2649.30		tr	3091.18	8	30
2659.5		1	3093.14	20	50
2668.26		2	3097.06	30	60
2669.84		6	3106.5		3
2672.90		8	3330.08	5	10
2695.53		1	3332.28	10	20
2698.44		2	3336.83	15	40
2732.35	1	5	3829.51	15	50
2733.80	5	10	3832.46	40	80
2736.84	8	12	3838.44	60	100
2765.47		2	3904.0	1	2
2768.57	1	5	3938.6	2	3
2776.80	3	12	3987.08	3	5
2778.36	2	10	4058.45	5	8
2779.94	10	15	4167.81	8	12
2781.53	3	10	4352.18	12	20
2783.08	2	10	4481.3	1	6
2790.88	10	20	4571.33	10	25
2795.63	80	80	4703.33	10	35
2798.07	15	20	4730.42	1	4
2802.80	60	60	5167.55 }	2	{ 15
2846.91	1	8	5172.87 }		{ 15
2848.53	2	10	5183.84	2	30
2852.22	500	500	5528.75		25
2915.57		tr	5711.38		2
2928.74	8	20			

arc under special conditions, either in air at a few millimeters pressure, in hydrogen, or in the "tube-arc" formed when the furnace tube is burned apart at a low voltage. In these sources λ 4481 appears with great intensity. Without further data on the state of the electric field producing the high-vacuum spectrum, it is perhaps useless to speculate on what features may bring about this difference.

The line λ 4571, faint in both arc and spark, is strong in the luminescence and in the anode spectra. This furnished the only point of similarity to the furnace spectrum, in which at low temperature λ 4571 dominates this region of the spectrum.

A high intensity of the Rydberg series of single lines is a notable feature of both of the high-vacuum spectra. The members in this list are λλ 5529, 4703, and λλ 4352–3987. Two other lines of this series appear, which have been observed by Fowler and Payn[1] in the vacuum arc. We have obtained these two lines also by prolonged exposure of the magnesium arc in air, the spectrum being formed by the 15-foot concave grating. Their wave-lengths were then measured as 3938.6 and 3904.0, close to the calculated values of the tenth and eleventh members of the Rydberg series.

Janicki and Seeliger[2] obtained several metallic spectra in a discharge at low pressure and observed the lines occurring near the anode and cathode respectively. Those in the positive column were the stronger arc lines, while in the cathode glow the spectrum contained also enhanced lines. Comparing their results for magnesium with ours, it is evident that the presence of enhanced lines in the luminescence spectrum and in that obtained with the anti-cathode connected as anode corresponds most nearly with conditions in the cathode glow spectrum of Janicki and Seeliger, even when we observed the vapor close to the anode. The vacuum employed by us was probably much higher than the vacuum they used, and the similarity to the cathode glow spectrum indicates that, with a high vacuum and the concentration of cathode particles which we have employed, the cathode emission is transferred to the focus of the stream at the anticathode. With magnesium the effect of the cathode bombardment at this point appears to be practically the same when the anticathode is also the anode.

CADMIUM

The cadmium luminescence spectrum shows a much closer similarity to that of the spark than was found for magnesium. The lines obtained are listed in Table IV, with their intensities, and also

[1] *Proceedings of the Royal Society,* **72,** 253, 1904.

[2] *Annalen der Physik* (4), **44,** 1151, 1914.

the arc and spark intensities given by Exner and Haschek. Three enhanced lines, λλ 3250.51, 3535.83, and 4415.89, are among the stronger lines of the luminescence spectrum. Certain strong arc lines are seen by the table to be greatly weakened in the luminescence.

The vacuum arc spectrum of cadmium was photographed for comparison, but no large difference from that of the arc in air was observed, the effects offering a decided contrast with those for magnesium, for which the spectrum of the arc in vacuum is more like that of the spark than is the luminescence spectrum.

TABLE IV

CADMIUM

λ (Exner and Haschek)	Lumi-nescence	Arc	Spark	λ (Exner and Haschek)	Lumi-nescence	Arc	Spark
2265.11........	6	2	10	3467.76........	3	50	15
2288.09*.......	50	500	10	3535.83........	4	1	4
2880.89........	2	10	3	3610.72........	40	500	100
2980.80........	3	30	3	3613.04........	5	50	15
3250.51........	30	......	10	4415.89........	100	1	20
3252.86........	1	20	3	4662.8.........	4	5	2
3261.23........	100	20	5	4678.38........	6	50	50
3403.86........	5	100	30	4800.14........	10	100	100
3466.33........	15	100	30	5086.06........	5	100	50

* Reverses widely in arc, with low photographic density. Not given in arc tables of Exner and Haschek.

A comparison with the results of Janicki and Seeliger[1] shows, as with magnesium, a qualitative correspondence with the spectrum of the negative glow, the lines strengthened in the luminescence spectrum being absent in that of the positive column.

CALCIUM

Two successful spectrograms for calcium with the quartz spectrograph confirmed the effects described in the former paper, the distinctive features being great intensity of λ 4227 and relatively high strength of the spark line-pairs and members of the single-line series. The position of the luminescence spectrum of calcium with reference to the arc and spark spectra is about the same as in the case of magnesium.

[1] *Loc. cit.*

ANODE SPECTRUM OF IRON

Several attempts to obtain the luminescence spectrum of iron yielded no better results than those reported in the former paper. An experiment in which the anticathode was made the anode, however, gave a spectrum of such distinctive character that it seems worth while to print a list of the lines which appeared and the results of a brief comparison with other sources. The vapor a few millimeters above the anticathode was photographed in the same way as when the anticathode was without anode connection. A current of 15 milliamperes was used, with a parallel spark-gap in air varying from 22 to 38 mm.

The lines of the spectrum thus obtained, with their intensities, are given in Table V. The effect is that of a picking out of certain arc lines, but this selection results in a spectrum apparently unique. Among its many differences from the ordinary arc or spark spectrum may be mentioned the extreme faintness of the triplets, whose strongest lines are at λ 4045 and λ 4383, and the absence of enhanced lines. Certain low-temperature lines are strong, λ 4376 being twice as strong as λ 4383, while $\lambda\lambda$ 4427, 4461, and 4482 are relatively prominent. This feature can be reproduced at low temperatures of the electric furnace, from 1500° to 1600° C., and in the low-temperature flames. In the furnace at this temperature, however, λ 4260 does not appear, and the very strong anode line λ 4227.45 belongs also to higher furnace temperatures. The vacuum arc spectrum of iron shows no approach to this high-vacuum spectrum. In the ultra-violet, while many of the strong lines are prominent also in arc, spark, and furnace, others are abnormally strong in the anode spectrum, and many arc lines of high intensity do not appear. The extension toward shorter waves is much beyond that reached by the high-temperature furnace, though the spectrum of the latter is richer in the region which it covers.

Plate XV illustrates the strongly selective action of the anode discharge as compared with the arc in air. The lines not belonging to iron are the manganese triplet at λ 4030 and several nitrogen bands. The latter occur in both the negative and the positive pole groups. The presence of the negative bands is another indication

PLATE XV

—4144

Mn—
—4046

—3930
N—
—3886
—3860
—3834
—3820
N—

—3764
—3745
—3735-7

—3720

N—

N—

—3491
—3475

—3441

a

b
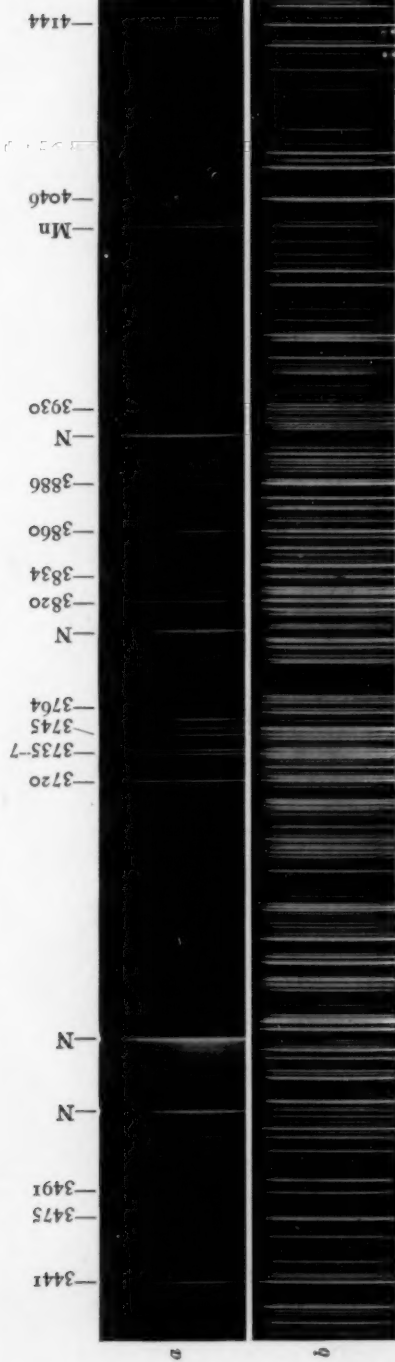
(a) Luminescence and (b) arc spectra of iron

of cathode conditions due to the pencil of rays focused here.   Both kinds of bands were found also when the anticathode was insulated.

TABLE V

ANODE SPECTRUM OF IRON

λ (I A)	I	λ (I A)	I	λ (I A)	I
2462.65.........	1	3465.86........	3	3859.91........	100
2472.91.........	1	3475.45........	8	3865.53........	1
2479.78.........	1	3476.71........	1	3872.51........	2
2483.28.........	10	3490.58........	15	3878.02........	2
2488.15.........	7	3497.11........	tr	3878.58........	5
2490.66.........	5	3497.84........	1	3886.29........	30
2491.16.........	2	3581.20........	8	3895.66........	2
2522.86.........	6	3608.86........	1	3899.71........	3
2527.44.........	3	3610.15........	1	3902.95........	2
2545.98.........	1	3618.77........	1	3920.26........	1
2549.62.........	2	3631.46........	2	3922.92........	6
2719.04.........	5	3647.85........	1	3927.93........	5
2720.91.........	2	3679.92........	7	3930.30........	5
2741.83.........	2	3687.46........	2	4045.82........	2
2749.49.........	4	3705.57........	12	4062.45........	1
2966.90.........	2	3709.25........	3	4063.60........	2
2981.45.........	tr	3719.94........	150	4066.98........	2
2983.57.........	3	3722.57........	10	4067.99........	1
2994.43.........	4	3727.62........	1	4071.75........	1
2999.52.........	35	3733.32........	4	4084.51........	1
3000.95.........	2	3734.87........	100	4198.31........	1
3008.14.........	1	3737.14........	100	4216.19........	2
3009.58.........	4	3745.56........	80	4227.45........	15
3018.99.........	1	3748.26........	20	4238.83........	1
3020.50		3749.49........	40	4247.44........	tr
3020.64 }	40	3758.23........	15	4258.39........	1
3021.08		3763.79........	5	4260.49........	2
3024.04.........	1	3767.19........	2	4271.76........	3
3025.85.........	1	3795.00........	2	4282.41........	1
3037.39.........	3	3812.97........	2	4307.91........	tr
3040.43.........	2	3815.84........	2	4325.77........	tr
3047.61.........	4	3820.43........	100	4375.93........	4
3057.45.........	20	3824.44........	10	4383.55........	2
3059.09.........	5	3825.89........	50	4404.75........	1
3067.25.........	5	3827.83........	tr	4427.31........	3
3286.76.........	1	3834.23........	15	4461.66........	2
3440.61.........	100	3840.44........	4	4482.26........	1
3440.99.........	50	3849.97........	1	4528.62........	2
3443.88.........	1	3856.37........	10		

SUMMARY OF RESULTS

Fairly rich spectra of manganese, titanium, iron, magnesium, calcium, and cadmium have been obtained by vaporizing the metal at the focus of a beam of cathode rays in a high vacuum and photographing the spectrum of the vapor in the path of the rays.   The

spectrum of iron was obtained by making the anticathode the anode, but photographs of the magnesium spectrum made in both ways indicated that, although the spectrum was more intense when the metal acted as anode, it did not differ in character from that produced with a separate anode so placed that the anticathode was out of the path of the current.

Comparison of these luminescence spectra with the arc, spark, and furnace spectra of the same elements shows that, although in general the majority of the lines are those easily excited in the arc and furnace, the following peculiarities mark this as a source having special characteristics:

1. Certain arc and furnace lines are intensified, while other lines, strong in these sources, are greatly weakened or are absent.

2. The resemblance to the spark spectrum, as measured by the tendency to give enhanced lines, differs greatly for different elements. The production of enhanced lines is very marked in the case of cadmium; they are present also to a considerable extent with magnesium and calcium, but to a very slight degree for titanium, manganese, and iron.

3. Where series relations are known, "single-line" series are likely to show a relatively greater intensity than other series lines.

4. There is a relatively high intensity of lines in the ultra-violet as compared with the arc and furnace spectra.

MOUNT WILSON SOLAR OBSERVATORY
March 1919

MONOCHROMATIC AND NEUTRAL-TINT SCREENS IN OPTICAL PYROMETRY

By W. E. FORSYTHE

It is very difficult to find a monochromatic or a neutral-tint glass screen. Very fortunately for optical pyrometry absolutely monochromatic or absolutely neutral-tint screens are not necessary. In general, for the so-called monochromatic screen, what is wanted is a screen that is sufficiently monochromatic to enable different observers to obtain very closely the same comparisons in brightness between the comparison source (or pyrometer filament for the Morse pyrometer) and the source that is being investigated.

In Fig. 1 is shown the spectral transmission of several red glasses. It has been found that two thicknesses of any one of the glasses whose transmission is shown by the curves B, C, and D give a transmission band sufficiently monochromatic to permit comparisons of brightness to be made between a pyrometer filament and a source, even where the color-difference corresponds to that of two black bodies operated at 1800° and 3100° K respectively. At the same time two thicknesses of each of the glasses whose transmissions are given by curves B and C transmit enough light to permit comparisons to be made for sources at very low temperatures.

The spectral transmission of the different pieces of glass was measured with the spectral pyrometer shown diagrammatically in Fig. 2. This instrument is quite similar to the one used by Henning.[1] The pyrometer filament was made of two-mil tungsten wire and was so mounted that the image formed by the lens at C was horizontal, while the slit was vertical. The background lamp consisted of a large, gas-filled tungsten lamp having a ribbon filament of about two millimeters' width. This filament was so mounted that its image at the slit was vertical, and of such width as to cover much more than the slit. To match the brightness of the image of this pyrometer lamp with the background it was found

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[1] *Zeitschrift für Instrumentenkunde*, **30**, 61, 1910.

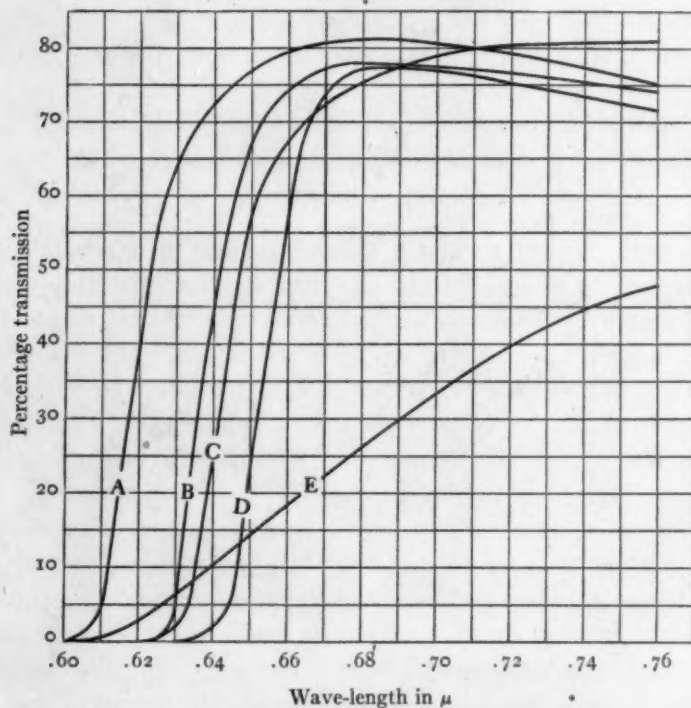FIG. 1.—Spectral transmission of various red glasses

Curve C for Jena red 4512, 2.93 mm thick.
Curve E for Jena red 2745, 3.2 mm thick.
Curve A for Corning high-transmission red, marked 150 per cent, 5 mm thick.
Curve B for Corning high-transmission red, marked 50 per cent, 5 mm thick.
Curve D for Corning high-transmission red, marked 28 per cent, 6 mm thick.
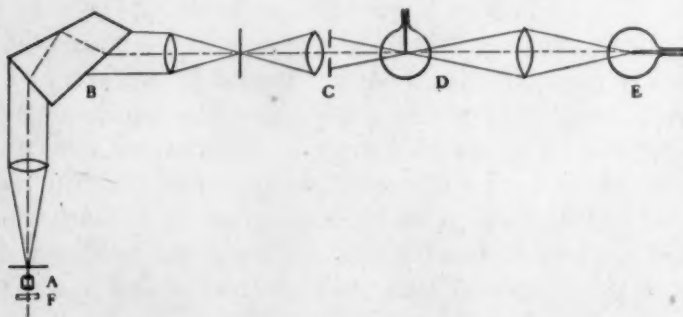
FIG. 2—Diagrammatic sketch of spectral pyrometer

necessary to have all the different parts well lined up. It was also necessary to use a diaphragm with a small opening at C for the more luminous parts of the spectrum. The opening in this diaphragm could be made larger for work at the ends of the spectrum, where the amount of light was much less. The image of the pyrometer filament, as seen through the eyepiece, had to be carefully focused for accurate work. As this depended somewhat upon the wave-length used, a scale was attached to the lens at C, so that it was possible to reset this at the proper place for the different parts of the spectrum after it had once been calibrated.

The ribbon filament background gave the very high bright-ness necessary for measuring transmissions that were as small as a fraction of 1 per cent. The glass whose spectral trans-mission was to be measured was mounted just in front of the pyrometer lamp. By making readings of the current through the pyrometer filament for an apparent match of brightness with the background, as seen first through the glass and then through sectors having very nearly the same transmission as the glass, it was possible to determine the transmission of the glass. Interpo-lated values were obtained by using the logarithms of the trans-mission of the sectors and of the current through the pyrometer lamp instead of the direct values, because the logarithms gave linear relations.

If the transmission of a piece of glass was measured over a range of wave-lengths and the currents through the pyrometer lamp plotted against wave-lengths, errors of measurements or sudden changes in the transmission of the glass were easily detected. To eliminate stray light a piece of colored glass was used at F. This was necessary when working in the extreme red or blue end of the spectrum. With this arrangement the transmission of different pieces of glass has been measured out to wave-length $0.76\,\mu$. It was found that if the collimator and eyepiece slits were 0.3 mm, corresponding to a range of $0.005\,\mu$ in the transmitted interval, the slit-width corrections would be negligible.

When it is necessary to use glass absorbing screens to reduce the apparent brightness of the source studied, the main requirement is to have a screen that approximates a neutral tint sufficiently well

to enable comparisons in brightness to be made by different observers with very approximately the same results. The degree to which it is necessary for the absorbing screen to have a spectral transmission independent of the wave-length depends upon the so-called monochromatic glass used in the eyepiece. It is quite evident that if this eyepiece glass is absolutely monochromatic any absorbing glass will answer.

In Fig. 3 are shown the spectral transmissions of a piece of noviweld (curve C) and of a piece of Jena absorbing glass (curve B). Either one of these glasses is nearly enough of neutral tint for
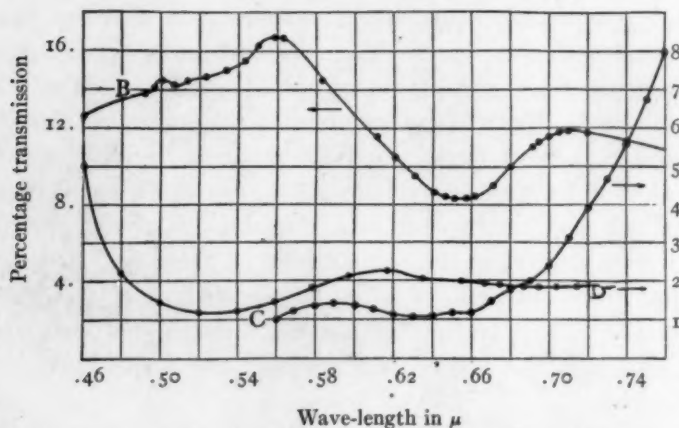
FIG. 3.—Spectral transmission of various absorbing glasses

Curve B—Jena absorbing glass 1.5 mm thick.
Curve C—Noviweld obtained from Corning Glass Works.   Shade about 6.
Curve D—Leeds & Northrup absorbing glass made of purple and green glass.

use with the red glasses whose transmission curves are shown by curves B, C, and D in Fig. 1. The noviweld absorbing glass and also the samples of Corning high-transmission red glass were obtained from Mr. F. P. Gage, of the Corning Glass Works. This absorbing glass is made in different shades, with transmissions, when used in connection with red glass, ranging from less than 1 per cent to several per cent.

If a red glass is used in the eyepiece, by total transmission for a particular temperature is meant the ratio of the brightness of the

source observed through both the red glass and the absorbing glass to the brightness of the same source observed through the red glass alone. Without a red glass, using the entire visible spectrum, it is generally very difficult to make such measurements, owing to the color-differences introduced by even the best absorbing glasses, but with a good red glass in the eyepiece measurements of transmission can be made easily.

The transmission of the absorbing glass when used with a red glass can be calculated for any black-body distribution by the following formula, taken from Preston's *Theory of Light:*

$$T_B = \frac{\int_0^\infty J_\lambda V_\lambda T_R' T_B' d\lambda}{\int_0^\infty J_\lambda V_\lambda T_R' d\lambda} \tag{1}$$

$J_\lambda d\lambda$ = black-body energy for interval λ to $\lambda+d\lambda$, V_λ = visibility, T_R and T_B' = spectral transmissions of the red glass and absorbing glass respectively. It is very evident that if the spectral transmission of the absorbing glass is different for different wave-lengths, the total transmission will be a function of the temperature of the source under investigation.

Experimental results.—First with two pieces of Jena red glass No. 4512 (spectral transmission shown by curve *C*, Fig. 1) and secondly with two pieces of Corning red 50 per cent (spectral transmission shown by curve *B*, Fig. 1) in the eyepiece of the pyrometer, readings were made on the apparent brightness of a particular source as observed through (1) a rotating sector with two one-degree openings; (2) the noviweld absorbing glass, whose spectral transmission is shown by curve *C*, Fig. 3, and (3) two pieces of the Jena absorbing glass, whose spectral transmission is shown by curve *B*, Fig. 3. The source used was a fifteen-mil tungsten lamp operated at a color temperature of 2610° K. The brightnesses were measured in terms of the current through the pyrometer filament for an apparent match of brightness. Four different observers made the measurements, three of them having had considerable experience with that kind of·work, and the fourth (K.H.M.) having had much less experience. Values thus obtained are given in Table I. The maximum range with the two glasses

occurs for K.H.M. and W.E.F. for the noviweld glass when the Jena red No. 4512 was used. This amounted to about 1 per cent in brightness and to less than five degrees in temperature at about 2500° K.

TABLE I

READINGS BY DIFFERENT OBSERVERS USING DIFFERENT RED GLASSES AND DIFFERENT ABSORBING GLASSES

OBSERVER	RED GLASS USED	CURRENT IN AMPERES THROUGH PYROMETER FILAMENT, FOR APPARENT MATCH OF BRIGHTNESS WITH:		
		2° Sector	Noviweld Absorbing Glass	Two Jena Absorbing Glasses
I.A.V............	Jena 4512	0.3358	0.3804	0.3547
K.H.M..........	Jena 4512	.3361	.3807	.3546
W.E.F...........	Jena 4512	.3361	.3803	.3546
A.G.W...........	Jena 4512	.3358	.3805	.3547
I.A.V............	Corning red	.3380	.3784	......
K.H.M..........	Corning red	.3380	.3785	......
W.E.F...........	Corning red	.3380	.3783	......
A.G.W...........	Corning red	.3378	.3784	......

For the currents given above, a change of 0.0005 ampere corresponds to a change of about 1 per cent in the brightness of the background. This same change in current through this pyrometer filament corresponds to about 4° K in temperature at about 2000° K.

The visibility-curves of the four observers are quite different, as can be seen by referring to a paper on "Visibility of Radiation" in the *Astrophysical Journal*, **48**, 65, 1918. Two of the observers (I.A.V. and K.H.M.) are quite blue-sensitive, one (W.E.F.) is somewhat red-sensitive, and the other (A.G.W.) is very much red-sensitive. These values extend toward the red end to wave-length 0.66 μ. In this work the visibility much beyond this point must be taken into consideration. It is not the visibility in the blue end of the spectrum that is important but rather the relative shapes of the different visibility-curves in the red end of the spectrum. In some other work[1] it was shown that, though there was a great variation in the values given by the individual observers to the brightness in the extreme red, the relative values do not vary so widely. From this it is to be expected that different observers will get very closely the same values of brightness if they are limited to the extreme red.

[1] *Astrophysical Journal*, **42**, 285, 1915.

In Fig. 4 is shown, as a function of the temperature of the source, the transmissions for red light of the absorbing glasses whose spectral transmission is given by curves *B* and *C*, Fig. 3. The measured points were determined by the author, and the calculated values were obtained by means of equation (1) by making use of an

Color temperature in degrees Kelvin
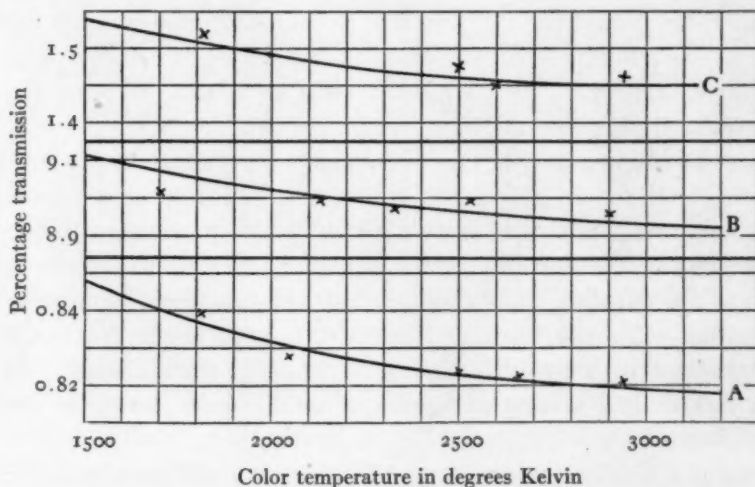
Fig. 4.—Transmission of absorbing glasses as a function of temperature when used with red glass No. 4512, 5.8 mm thick.

Curve A.—Two pieces Jena absorbing glass.
Curve B.—One piece Jena absorbing glass.
Curve C.—Noviweld glass from Corning Glass Works.

Curves drawn through points calculated from equation $T_B = \dfrac{\int_0^a J_\lambda V_\lambda T'_R T'_B d\lambda}{\int_0^a J_\lambda V_\lambda T'_R d\lambda}$.

Crosses represent values of transmission obtained with optical pyrometer.

average visibility-curve[1] for this spectral region. Values of transmission were also calculated, using the observer's visibility-curve. Values thus obtained, using the two different visibility-curves, differ from each other by only a small fraction of 1 per cent.

Inasmuch as a question has been raised[2] concerning the accuracy of the results thus obtained, a word might be said concerning this method of calculating values of transmission. In using equation

[1] *Astrophysical Journal*, **48**, 87, 1918.
[2] *Bulletin of the Bureau of Standards*, **12**, 485, 1916.

(1) in this work, as well as in determining the effective wave-length, the integral was found by the step-by-step method. Results can be obtained that are as accurate as desired by making the steps small enough. If the two-thirds rule is used very accurate results can be obtained with fewer steps. Transmission values can thus be obtained that are as accurate as the data warrant. If the computation be carried too far, and if such values of transmission are used in determining the effective wave-lengths, the latter will, of course, appear to be extremely accurate, more so than the experimental data warrant.

An absorbing glass that is not strictly of neutral tint is frequently used to cut down the apparent brightness of a source when measuring its temperature with an optical pyrometer having a red glass in the eyepiece. It has been stated[1] that a different value of the effective wave-length of the red glass must be used in connection with the so-called neutral-tint glass from that used in connection with a rotating sector of the same transmission. In what follows it is shown that such is not the case, but that the same effective wave-length is to be used for both.

Suppose that, using the same red glass in both cases, a sector with a transmission T_S were found such that the brightness observed through the black glass would equal that observed through the sector (i.e., sector and glass have same transmission). Then

$$\int J_\lambda V_\lambda T_B' T_R' d\lambda = \int J_\lambda V_\lambda T_R' T_S d\lambda = T_S \int J_\lambda V_\lambda T_R' d\lambda .$$

Since the brightness is measured in terms of the current through the pyrometer filament, this current will be the same in the two cases. This means that in both cases the temperature T_2 that is being determined must be calculated from the same initial temperature.

The question to be considered is what effective wave-length is to be used in calculating the temperature of the source whose brightness is thus measured. When the brightness is measured with the use of the rotating sector the temperature T_2 is calculated from the transmission of the sector and T_1, the temperature corresponding to

[1] *Bulletin of the Bureau of Standards*, 12, 483, 1916.

the pyrometer reading when no sector is used. For this calculation the following formula derived from Wien's equation is used:

$$1/T_2 - 1/T_1 = \frac{\lambda_e \log T_S}{C_2 \log e}. \tag{2}$$

In this expression λ_e is the ordinary effective wave-length between T_1 and T_2 and is defined as the wave-length such that the ratio of the intensities of radiation for the temperature-interval for this wave-length shall equal the ratio of the integral luminosities through the screen used, or, stated in the form of an equation,

$$\left(\frac{J(\lambda T_1)}{J(\lambda T_2)}\right)_{\lambda_e} = \frac{\int J(\lambda T_1) V_\lambda T'_R d\lambda}{\int J(\lambda T_2) V_\lambda T'_R T_S d\lambda}. \tag{3}$$

When the brightness is measured with the use of an absorbing glass, the temperature T_2 must be calculated from the transmission of the absorbing glass and T_1, the temperature corresponding to the pyrometer current when no absorbing glass is used. Inasmuch as we know the ratio of the brightness of the black body at the unknown temperature T_2 to that of the black body at temperature T_1, the temperature T_2 is to be calculated by an equation similar to equation (2), that is, by

$$1/T_2 - 1/T_1 = \frac{\lambda'_e \log T_B}{C_2 \log e}, \tag{4}$$

where λ'_e is an effective wave-length. As T_1 and T_2 are the same in equations (2) and (4),

$$\lambda_e \log T_S = \lambda'_e \log T_B,$$

whence

$$\lambda_e = \lambda'_e.$$

That is, since the transmission of the absorbing glass given by equation (1) is the same as that obtained experimentally by comparing its transmission with that of a sector, the same effective wave-length of the red glass is to be used with both the absorbing glass and a sector having the same transmission.

Thus to calculate the extrapolated brightness-temperature of a source whose brightness is measured through a black glass, it is necessary to know the transmission of the glass as a function of the

temperature of the source studied, and also the ordinary effective wave-length, defined by equation (3), for the red glass used. In calculating the extrapolated temperature when using a sector disk, it is necessary to know this temperature very approximately in order to find the effective wave-length for the interval. The calculation is therefore one of successive approximations. When a so-called neutral-tint glass is used, additional care is required, because both the effective wave-length and the transmission depend upon the temperature reached. When the effective wave-length of the red glass and the transmission of the absorbing glass are known, the extrapolated temperature is calculated by means of equation (4).

In Fig. 5 are shown the extrapolated temperatures that are obtained with the absorbing glasses whose transmissions are shown in Figs. 3 and 4. These values were obtained from equation (4) and the transmissions of the different glasses as shown in Fig. 4. The dotted line under each curve shows what the resulting temperature would be if the transmission of the glass did not vary with the temperature of the source but remained the same at high temperatures as was found for the lower temperatures. For the Jena absorbing glass this change amounted to only 3° K for a range from 1900° K to 2400° K, and for the noviweld glass the change amounted to 8° K for a range from 1900° K to 3000°K. These two glasses were the best ones found among those investigated. The spectral transmission of the glass obtained from Leeds & Northrup, given in Fig. 3, curve *D*, shows that this glass would give almost the same results as a sector. Lack of time prevented a complete test of this glass.

Only one absorbing glass was tested that gave any trouble due to lack of color-match of the pyrometer-lamp filament at a temperature of 1800° K and a background at 3000° K. This glass had an almost uniform spectral transmission of about one-half of 1 per cent from 0.60 μ to 0.65 μ, and from there on to longer wave-lengths increased very rapidly, being about 5 per cent at 0.68 μ, 20 per cent at 0.70 μ, and 40 per cent at 0.72 μ. Thus, in general, if a good red glass is used in the eyepiece of the pyrometer but little trouble is experienced in obtaining an absorbing glass that is satisfactory for extrapolation of the temperature-scale.

Attempts have been made to obtain an absorbing glass that is of strictly neutral tint, or even one that has such a transmission as to correct for the change in effective wave-length of the red glass used.
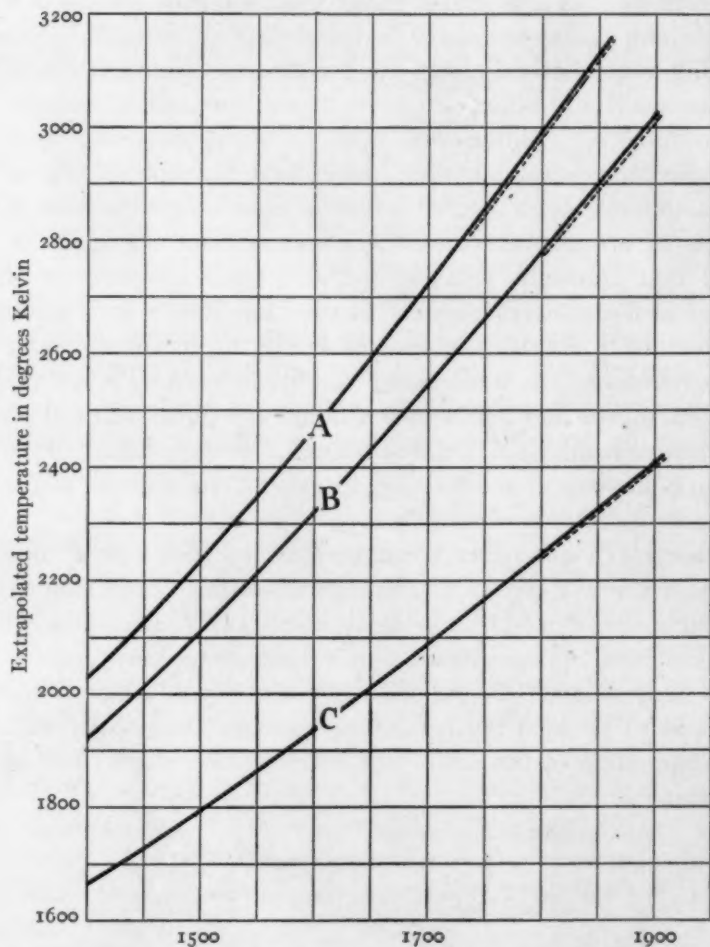
Temperature in degrees Kelvin corresponding to pyrometer lamp current if no absorbing glass or sector is used.

FIG. 5.—Curves showing extrapolated temperature given by various absorbing glasses.

Curve A.—Two Jena absorbing glasses.

Curve B.—One Jena absorbing glass.

Curve C.—Corning noviweld—shade about 2.4.

If obtained, this would probably be very good, but it is not at all necessary. What is wanted is a glass that will permit comparisons of brightnesses to be made by different observers with very nearly the same result. It was shown above that if a good red glass is used absorbing glasses can easily be found that are suitable. The same thing might be said about the red glasses. Many attempts have been made to obtain absolutely monochromatic screens for optical pyrometry. This is very good for some purposes, but is not necessary in general, and such glasses have the disadvantage of not transmitting enough light to permit of accurate comparisons of brightness at low temperatures. A good red glass can easily be obtained that transmits enough light to permit comparisons of brightness at low temperatures and at the same time is sufficiently monochromatic to enable different observers to obtain the same results, even under the unfavorable conditions existing when the comparison source and the source studied are quite different in temperature. In addition to this, if the effective wave-length of the red glass is known, all results can, in general, be reduced to the condition for a common wave-length.

Summary.—In this paper it has been shown that with a good red glass in the eyepiece of pyrometers absorbing glasses can be found that are near enough to being of neutral tint so that different observers obtain the same values of measured temperature. It has also been shown that the same effective wave-length of the red glass is to be used both with the rotating sector and with an absorbing glass of the same total transmission that is not of neutral tint.

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STUDIES BASED ON THE COLORS AND MAGNITUDES IN STELLAR CLUSTERS

ELEVENTH PAPER: A COMPARISON OF THE DISTANCES OF VARIOUS CELESTIAL OBJECTS

By HARLOW SHAPLEY

The bearing that parallaxes of clusters and variable stars may have on the general structural problems of the sidereal system is well illustrated through a tabulation and diagrammatic representation of the distances of various remote celestial objects. Part of the data compared has been obtained directly or indirectly from the statistical investigations of Kapteyn, Charlier, and Dyson, and from recent trigonometric parallaxes, mainly by van Maanen, but the greater part is from the observations discussed or summarized in the preceding contributions or from similar work that will be reported more fully at another time.

Table I summarizes the distances illustrated in Fig. 1. On the scale of the diagram objects as near as the Hyades or the brighter naked-eye stars can be shown only with difficulty, even when the lines representing distances of clusters are folded many times. The accuracy of the values in the second column of the table differs considerably, and for only a few, which are averages for many objects, is there any meaning in the third significant figure. For some of the results the relative certainty is indicated in the last column, but for most of them reference must be made to the brief discussion of the individual entries to which the remainder of this paper is devoted. Special attention may be called to Section J, which contains a discussion of pre-giant stars and the variables of the Orion nebula.

A, 1. *The most distant globular cluster.*—The four most distant clusters now known are N.G.C. 7006, 4147, 6266, and 6316; the adopted parallaxes in millionths of a second are 15, 19, 19, and 20, respectively, corresponding in the mean to a distance of 55,000 parsecs (180,000 light-years). For N.G.C. 4147 the adopted value

depends upon measures of both magnitudes and diameter, for the others on diameter alone; but, subsequent to the preparation of

TABLE I

COMPARISON OF THE DISTANCES OF VARIOUS STARS, CLUSTERS, AND NEBULAE

Object	Distance (Unit is 100 parsecs)	Remarks
A. Globular clusters:		
1. Most distant cluster........	670	N.G.C. 7006
2. Diameter of typical system..	1.5	Messier 3
3. Nearest cluster............	65	ω Centauri
4. Mean distance.............	230	69 clusters
5. Maximum $R \sin \beta$........	500	N.G.C. 4147
6. Minimum $R \sin \beta$........	13	N.G.C. 6656 (M 22)
B. Distance covered in a million years by constant velocity of 1180 km/sec.............	12	
C. Cepheid variables:		
1. Most distant.............	60	Three stars
2. Maximum $R \sin \beta$, periods less than a day...........	29.3	Mean of five
3. Mean $R \sin \beta$, periods less than a day..............	9.63	45 variables
4. Mean $R \sin \beta$, periods greater than a day..............	1.48	94 variables
D. Eclipsing binaries:		
1. Most distant.............	31	Mean of five
2. Mean distance...........	7.6	90 variables
E. Galactic clouds near Messier 11	50	Four fields
F. Messier 37..................	40	Preliminary estimate
G. Small Magellanic Cloud:		Provisional values from variable
1. Radial distance...........	190	stars
2. Approximate diameter......	15	
3. $R \sin \beta$.................	130	
H. Three galactic novae.........	1.1	Direct measures
I. Nebulae (van Maanen):		Direct measures with 60-inch
1. Two spirals..............	2	reflector
2. Three planetaries........	0.7	
J. Orion nebula (Kapteyn)......	1.9	*Mt. Wilson Contr.* No. 147
K. Hyades (Boss, Kapteyn)......	0.4	
L. Most distant naked-eye star...	10	
M. B-type stars (Charlier):		
1. Most distant.............	8.5	Mean of five
2. Dispersion in galactic plane.	1.8	751 stars
3. Diameter of system........	10.0	Including 95 per cent of stars
N. Distance of sun from center:		
1. Of system of globular clusters	200	69 clusters
2. Of system of B-type stars...	0.9	751 stars of Charlier's cluster
O. Width of equatorial segment...	35	Arbitrarily chosen; see note 1,p,5

the seventh paper, the parallax of N.G.C. 7006 has been studied by means of the magnitudes of the brightest stars (p. 14, n. 1, of seventh paper), and for the present, at least, its distance seems

definitely to be the greatest known.   Further work on the colors and magnitudes, to test if this remote system is actually comparable to the nearer globular clusters, is described in the following paragraphs.
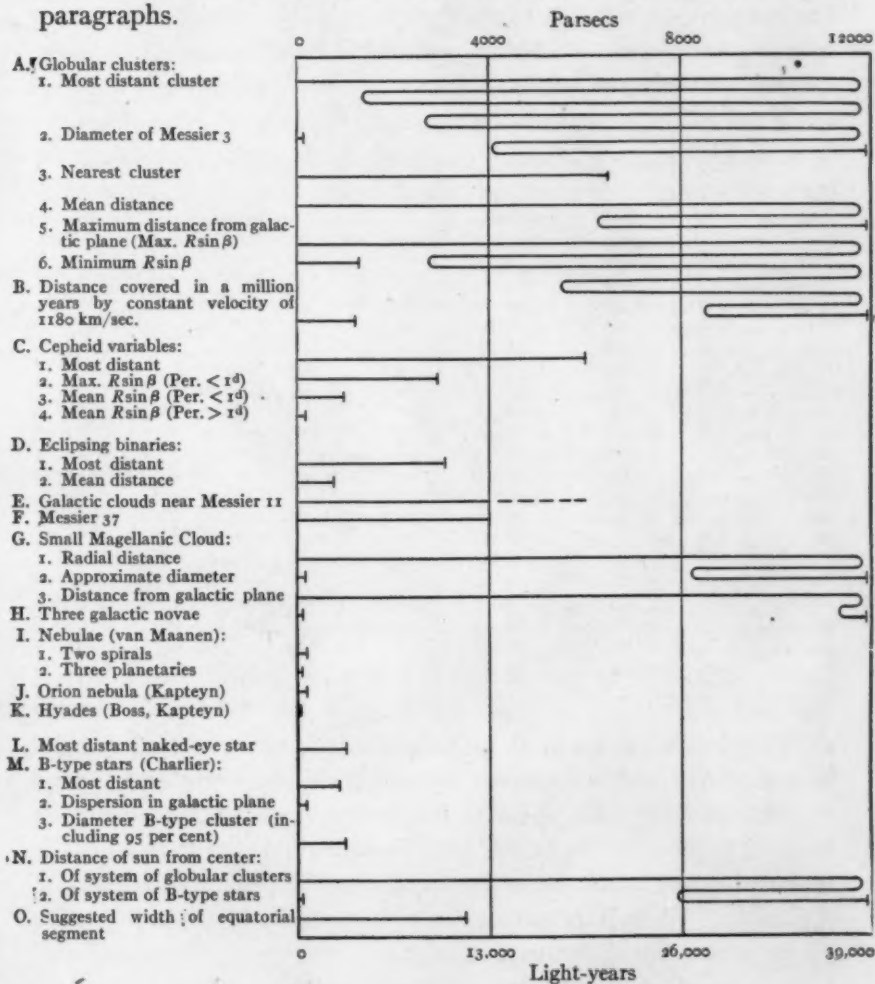
FIG. 1.—Comparison of distances in the galactic system

Since in N.G.C. 7006 the stars of zero absolute magnitude are probably of the nineteenth apparent magnitude, it is very difficult to extend the investigation of photo-visual brightness to any but the most luminous red giants.   The extremely small apparent

diameter also introduces difficulties of measurement and liability to systematic error if the central part is not carefully avoided.

Table II contains a list of all the stars between 0.′3 and 1.′0 from the center that could be measured on a photo-visual plate of 45 minutes exposure. Probably not more than two or three non-cluster stars are included.

TABLE II

MAGNITUDES OF THE BRIGHT STARS IN N.G.C. 7006

Star	Pg. Mag.	Pv. Mag.	Star	Pg. Mag.	Pv. Mag.
17........	17.06	15.76	37........	17.19	16.27
18........	17.15	15.64	38........	17.53	16.51
19........	17.13	16.27	39........	16.85	15.76
20........	17.40	16.42	40........	17.97	16.71
21........	17.93	16.98	41........	18.01	17.37
22........	18.01	16.79	42........	16.89	15.90
23........	17.80	16.95	44........	17.89	16.97
24........	17.89	16.86	45........	17.76	16.76
25........	18.01	16.97	46........	17.93	16.60
26........	17.53	16.32	48........	17.89	16.46
27........	17.69	16.79	49........	17.83	16.57
28........	17.31	15.77	50........	18.39	17.32
29........	16.29	15.26	51........	17.49	16.90
30........	16.99	16.42	52........	17.62	16.51
31........	17.58	16.26	53........	17.76	16.46
32........	16.21	15.71	54........	17.26	16.19
33........	17.31	15.71	55........	18.21	17.01
34........	16.87	15.45	56........	18.04	16.77
35........	17.61	16.90	57........	16.99	16.45
36........	17.76	16.46			

The results are grouped in Table III according to photo-visual magnitude in order to show, as far as the data go, the typical decrease of color with absolute brightness. Star No. 32, being at some distance from the center and peculiarly blue for its magnitude, is probably not a member of the cluster and has been excluded from the table. Were it retained, the first mean magnitude would be 13.59, with a corresponding color-index of $+1.23$. The table also contains analogous data[1] for Messier 3 and 13. The frequency of stars of high luminosity is much the same in the three systems; further, the mean color-index is the same for the brighter stars and shows for all clusters a similar progressive decrease. Hence this very distant faint cluster of small angular diameter apparently

[1] One bright star in Messier 13, with color-index -0.52, is excluded.

differs no more in constituency and stage of development from the nearer systems than they differ among themselves. But as far as our present photometric study is concerned, N.G.C. 7006 is nearly two hundred thousand years younger than Messier 13—a significant phenomenon that will be considered further in the following paper.

The evidence of Table III bearing on the question of the scattering of light in space is of considerable interest. Granting the physical similarity of the three clusters, we find no appreciable difference in color on account of the much greater distance of

TABLE III

COMPARISON OF N.G.C. 7006 WITH MESSIER 3 AND 13

N.G.C. 7006			MESSIER 3			MESSIER 13		
Mean Pv. Mag.	No. of Stars	Mean Color-Index	Mean Pv. Mag.	No. of Stars	Mean Color-Index	Mean Pv. Mag.	No. of Stars	Mean Color-Index
15.56..	5	+1.37	12.59..	7	+1.30	12.11.,.	6	+1.31
16.02..	6	+1.14	12.90..	5	+1.18	12.47..	7	+1.14
16.41..	7	+1.04	13.10..	7	+1.61	12.72..	5	+0.94
16.55..	6	+1.16	13.43..	9	+1.12	12.87..	6	+0.82
16.82..	7	+0.96	13.70..	7	+0.99	13.05..	6	+0.92
17.08..	7	+0.95	(13.90..	13	+0.96)	13.14..	6	+0.93
16.46..	38	+1.09	13.17..	35	+1.15	12.72..	36	+1.02

N.G.C. 7006. The total effect of interstellar media on the color-indices of stars in this most distant system apparently does not much exceed a tenth of a magnitude. Therefore the "absorption coefficient," expressed as change of color-index for each parsec of distance, is

$$d < 0.000002 \text{ mag.},$$

a value but one-fifth the upper limit found from the study of nearby globular clusters and a hundredth the smallest value derived from the parallaxes and colors of isolated bright stars. We note, however, that the galactic latitude of N.G.C. 7006 is $-20°$, so that only 8 per cent of the light-path lies within the equatorial segment[1] devoid of globular clusters. If we assume that all the diminution

[1] The adopted width of the segment is 3500 parsecs; in Figs. 4 and 5 of the seventh paper the shaded area representing the mid-galactic segment is 4000 parsecs wide, but includes five clusters. For Messier 13 one-fourth of the light-path is within this region.

of light through scattering (if there be any at all) occurs within this region where stellar matter appears to be greatly concentrated, the value of d is still sufficiently small to be safely ignored in all ordinary stellar problems.

The magnitudes of Table III can be used for a new determination of the parallaxes of Messier 13 and N.G.C. 7006. The parallax of Messier 3, being one of the best determinations for any globular cluster, is adopted for the computation. Assuming that stars of the same absolute magnitude are involved in the final means for each cluster, we derive readily:

$$
\begin{aligned}
\text{Messier 3,} \quad & \pi = (0.''000072) \\
\text{Messier 13,} \quad & \pi = 0.000089 \\
\text{N.G.C. 7006,} \quad & \pi = 0.000016
\end{aligned}
$$

The previously adopted parallaxes of the last two clusters are 0.''000090 and 0.''000015, respectively. It is to be noted that the present result is based upon photo-visual magnitudes, and that the five brightest stars of each cluster have not been excluded. The almost exact agreement with the former values merely shows that the similarity in the amount and frequency of color among the giant stars in clusters makes photo-visual as well as photographic magnitude a fairly definite criterion of distance.

A, 2. *The diameter of Messier 3.*—In the seventh paper of this series appears a discussion of the size of globular clusters. The occurrence of cluster stars far beyond the limits shown by the usual photograph has been inferred by Bailey and others from the distribution of cluster-type variables. We have recently found, however, that among galactic stars the variables of this type are peculiar in their occasionally great distance from the galactic plane, and for the five so far investigated the radial velocity is abnormally high. Is it possible that high velocity or some other cause has also scattered the short-period variables of clusters beyond the domain occupied by other cluster stars? To answer this question long-exposure photographs of the brighter systems are being made, with the clusters 15' or 20' out of center. The counts so far available show many faint cluster stars as far from the center as any of the variables. The angular diameter of Messier 15, for instance,

appears to be not less than 35′, corresponding to a linear diameter of 150 parsecs. These counts indicate, first, that the stars of the outer parts of clusters may be systematically fainter, smaller, and less massive than those close to or at moderate distances from the center; secondly, that the space outside the equatorial galactic region may be occupied not only by occasional cluster-type variables but also by other isolated stellar bodies that possibly are relatively faint; for the time being, however, both suggestions must be regarded as tentative.

A, 3. *The nearest globular cluster.*—The parallax of ω Centauri ($\pi=0''00015$) is uncertain because of the provisional nature of the magnitudes of the variables and bright stars. The adopted parallax of 47 Tucanae (N.G.C. 104) is nearly as large, but it is also lacking in precision, being derived from an uncertain part of the parallax-diameter curve.[1] The distances of both clusters can be very accurately determined when the variables have been further studied, but for the present an uncertainty of some 30 per cent may affect the adopted values. In general the largest as well as the very smallest cluster parallaxes are of relatively low accuracy, depending completely or in part upon the extremities of the curve relating parallax to diameter.

A, 5. *Maximum distance from the plane of the Galaxy.*—Five globular clusters are more than 20,000 parsecs from the galactic plane, but the small faint cluster N.G.C. 4147 in galactic latitude $+78°$ is nearly twice as remote from the dense stellar regions as the next most distant system. Its peculiar position in space suggests the possibility of peculiarity in structure and content—perhaps in this case the methods of determining distance may not be strictly applicable. The adopted parallax appears to be of the right order, however, as the survey of the colors of the brightest objects in the cluster (Table IV) indicates that we are dealing with typical giants; but a deficiency in the number of giant stars is indicated by this table, and long exposures on fast plates suggest a deficiency of faint stars as well. Further, Table II of the seventh paper contains evidence that the angular diameter is somewhat small for the magnitude of the bright stars.

[1] *Mt. Wilson Contr.* No. 152, Fig. 1.

This discrepancy between the values of the parallax of N.G.C. 4147 as based on the provisional magnitudes and on the estimates of diameter was considered unimportant until a verification of the earlier value of the mean magnitude was obtained through a recent study of additional plates. It now appears that the adopted parallax may be a few millionths of a second too small, and the distances given in the diagram and in Table I of this paper may be somewhat too large. Because of its high galactic latitude, however, the cluster will probably remain the most isolated of known systems, even when further work on the colors permits a definite revision of the parallax.

TABLE IV

COLORS AND MAGNITUDES OF GIANT STARS IN N.G.C. 4147

Star	Pv. Mag.	Color-Index	Star	Pv. Mag.	Color-Index
1.........	14.66	+0.99	18.........	15.74	+0.51
2.........	15.31	+0.71	22.........	13.59	+1.83
3.........	15.62	+0.76	23.........	15.92	+0.41
5.........	15.89	+0.08	24.........	15.33	+0.97
6.........	14.74	+1.08	29.........	15.95	+0.70
11.........	15.92	+0.69	30.........	15.81	+0.42
13.........	15.76	+0.52	35.........	15.74	+0.73
17.........	15.53	+0.76			

B. *Distance traversed in a million years by maximum velocity.*— The highest speed of translation so far recorded for any celestial object is 1180 km/sec.—the mean radial velocity of the spiral nebula N.G.C. 4594.[1] The corresponding entry in Fig. 1 permits an easy consideration of the possible past and future relationship of the various sidereal bodies. The greatest radial velocity recorded for a globular cluster is about one-third of the foregoing value and for isolated stars about one-half.[2] For discussions of this nature it is convenient that a velocity of a kilometer a second is very nearly equivalent to a velocity of a parsec in a million years.[3]

C. *Cepheid variables.*—The data for Cepheid variables of the galactic system are from Tables I and I a of the eighth paper of this

[1] Pease, *Mt. Wilson Communication*, No. 32; *Proc. Nat. Acad. Sci.*, **2**, 517, 1916.

[2] See Table I of the following paper.   [3] More exactly it is 1.02 parsecs.

series. The three most distant are VX Cygni, RU Boötis, and SW Herculis, the last two being cluster-type variables. The difference in the dispersion with respect to the galactic plane is well illustrated by C, 3 and C, 4 for Cepheids of short and long period, respectively.

The maximum $R \sin \beta$ for Cepheids with periods less than a day is the mean of the values for RU Boötis, SW Herculis, 169.1907 Leonis, RR and RU Canum Venaticorum; it is much greater than the adopted semi-width of the equatorial segment that is devoid of globular clusters. The corresponding value of maximum $R \sin \beta$ for periods greater than a day (excluding Z Canum Venaticorum) is 6.70.

D. *Eclipsing variables.*—With a few revisions based upon later orbital computations, the data for eclipsing binaries are taken from a paper by Russell and Shapley.[1] The five most distant variables are W Crucis, SS Carinae, UZ Cygni, RV Persei, and VV Cygni. The quantity designated as the average distance in the diagram in the *Publications of the Astronomical Society of the Pacific* for February, 1918, is the distance corresponding to the mean parallax— a quantity that, because of the wide range of values, is less than half the mean distance now computed.[2]

The parallaxes of eclipsing binaries, even of those with well-determined light-curves and spectra, are somewhat less accurately known than the parallaxes of average Cepheid variables. They depend upon the apparent magnitude, mass, surface-brightness, and radius of the brighter component of the eclipsing pairs, and in the evaluation of some of these quantities approximations are necessary. For the most favorable cases, however, the estimated error in the hypothetical parallaxes is not in excess of 25 per cent, and is essentially independent of the distance.

Direct measures of the parallax of several eclipsing stars, while yielding results of the same order of magnitude as the probable errors, serve to confirm the hypothetical values. Nearly all of the direct determinations have been made by various observers at the

[1] *Astrophysical Journal*, **40**, 417, 1914.

[2] In addition to the inclusion of more objects, the present diagram differs from the earlier one in several minor details.

Yerkes Observatory;[1] a summary of their results is given in Table V.

On the average the hypothetical parallaxes differ from the trigonometric values (corrected for comparison-star parallax by means of the Greenwich table)[2] by less than the probable error of the direct measures; systematically they are $0''002$ larger than the trigonometric results. The mean trigonometric parallax of β Persei, using all sources, is $+0''034\pm0''011$. For β Aurigae, an eclipsing binary not on the Yerkes list, the mean value of the parallax by

TABLE V

COMPARISON OF HYPOTHETICAL AND TRIGONOMETRIC PARALLAXES OF ECLIPSING BINARIES (YERKES RESULTS)

Star	Measured by	Trigonometric Parallax (Abs.)	Probable Error	Hypothetical Parallax	Difference
β Persei.......	Lee	$+0''025$	$\pm0''014$	$+0''026$	$-0''001$
W Ursae Majoris	Lee	$+0.011$	±0.010	$+0.020$	-0.009
U Ophiuchi....	Joy	-0.008	±0.004	$+0.006$	-0.014
Z Herculis.....	Van Biesbroeck	$+0.031$	$\pm0.009^*$	$+0.009$	$+0.022$
RX Herculis...	Van Biesbroeck	-0.006	±0.016	$+0.006$	-0.012
Y Cygni.......	Mitchell	$+0.004$	±0.010	$+0.004$	0.000
Mean.........			±0.0105		±0.0097

*The probable error is given as $\pm0''010$ in the collected results, p. 57, of *Yerkes Publications*, 4, Part I.

three observers is $+0''034\pm0''015$; the hypothetical value is $+0''030$, and if the star is a member of the Ursa Major group its parallax is $+0''025$.[3] By entering these two mean values in Table V the small systematic difference disappears.[4]

As a class the eclipsing variables are too remote for direct measures of parallax, but the foregoing comparison for the nearer ones shows that the method based upon orbital data is adequate to locate them in space with considerable certainty.

[1] *Publications of the Yerkes Observatory*, 4, Part I, 1917.

[2] Dyson and Thackeray, *Monthly Notices*, 77, 14, 1916. The Greenwich values should all be decreased by 10 per cent if instead of 19.5 km/sec. we adopt for the velocity of the sun the value given in Sec. 2 of the sixth paper. The correction is unimportant in the present case.

[3] Erroneously printed as $+0''019$ in *Astrophysical Journal*, 40, 425, 1914.

[4] *Note added to proof.* An overlooked parallax of u Herculis by Miller: Trig. π (abs.) $= -0''026$, hyp. $\pi = +0''005$.

E. *Galactic clouds.*—The study of the colors of stars near Messier 11 indicates the great extent of the galactic clouds in the line of sight;[1] the maximum distance so far estimated depends only on the limit of magnitude attainable on the photo-visual plates. Photographs of the field of Messier 11 are now available for the extension of this work to the fainter and more remote stars. It appears very probable, from the preliminary results, that isolated stars as distant as 30,000 parsecs may be found near the galactic plane in these southern star clouds.

F. *Messier 37 (N.G.C. 2099).*—This northern object, one of the richest of the bright open clusters, is situated near the galactic plane, almost diametrically opposite the point of concentration of globular clusters. A catalogue, now in manuscript, of the magnitudes and colors of several hundred of its stars will be published later as a paper of this series.

G. *Magellanic clouds.*—The adopted parallax of the Small Magellanic Cloud is that given in Table I of the seventh paper— a value undoubtedly of the right order but one which will be replaced by a value of much greater weight when the magnitudes of the variables have been referred to a standard system. The adopted mean angular diameter is $4°.5$, representing the region throughout which the variable stars belonging to the cloud are distributed. We infer from the similarity of the provisional magnitudes of the variables that the distance of the two Magellanic Clouds is of the same order, but the Larger Cloud covers more than double the area.

H. *Galactic novae.*—The three objects for which directly determined parallaxes are available are Nova Persei No. 2, Nova Lacertae, and Nova Geminorum No. 2. The derivation of the adopted mean value of $+0''.009$ will be discussed by van Maanen in a forthcoming contribution.

I. *Spiral and planetary nebulae.*—The direct measurement of the parallaxes of nebulae will be considered by van Maanen in the same paper. He attaches little weight to the measured results for the spirals because of the non-stellar character of the central nuclei. One of the spirals is the Great Andromeda Nebula (N.G.C. 224);

[1] The fifth paper of this series, *Mt. Wilson Contr.* No. 133, 1917.

the other is Messier 51 (N.G.C. 5194). The planetaries are N.G.C. 2392, 6720, and 7662. The adopted parallax of N.G.C. 6720, the ring nebula in Lyra, is the mean of the values by van Maanen and by Newkirk.

J. *The Orion nebula.*—On the basis of his exhaustive study of the motions of the B-type stars, Kapteyn adopts as the parallax of the "nebula-group" in Orion:

$$\pi = 0''.0054 \pm 0''.0009.$$

That the same parallax is the best available for the nebula itself can hardly be doubted.

It does not seem to have been pointed out that if the numerous variables of the Orion nebula are a part of the nebula-group we have in them a remarkably large assemblage of stars of low luminosity. Of more than 100 stars within two or three degrees of the trapezium that are supposed to be definitely variable, nearly all are fainter than the fourteenth photographic magnitude at maximum, and many never become brighter than the fifteenth magnitude. With a parallax of 0''.005 the average absolute brightness at maximum is only about a tenth that of the sun, and at minimum less than a twentieth. Apparently they are dwarfs, while all other variable stars—Cepheids, eclipsing binaries, long-period variables (at maximum)—are typically objects of high luminosity.

The possibility that in the faint variable stars of Orion, which appear to be intimately associated with diffuse nebulosity, we have examples of stars in the pre-giant stage of stellar evolution, led to the initiation, nearly four years ago, of systematic observations of their magnitudes and colors. Such variables might be of considerable importance, for if Russell's theory of the evolutionary sequence of spectral types be accepted and we desire to find a record of the parentage and earliest development of the relatively young, highly luminous, low-temperature and low-density red giant stars, it seems obvious that we should look for (1) objects varying in light secularly or irregularly rather than with definite period and amplitude; (2) objects closely associated with the matter from which typical stars originate—nebulosity, we usually say, that is formless or in

a quite chaotic state; (3) objects of faint absolute magnitude and low-surface temperature, therefore very red and possibly with striking peculiarities of spectrum. At least some of these properties are naturally thought of as attributes of the pre-giant stage; and the Orion variables appear upon first examination to be promising subjects for inquiry.

If, however, we cannot find satisfactory evidence of pre-giants among such stars as the Orion variables, the typical long-period variables, or the occasional irregular variables that are associated with variable nebulosity, there remain at least three ways (before we need abandon Russell's theory) in which we may attempt to account for the absence from our present records[1] of recognized visible forerunners of the low-density red giants. We may suppose (1) that the normal transformation of an invisible nebular mass to a highly luminous star is infrequent as compared with the rapidity of the change; astronomical history is so brief, on that hypothesis, that it contains as yet no definite record of a secularly brightening red star or of the occurrence of a red nova that maintains its maximum; or (2) that the phenomenon of rising luminosity, and hence of the birth of a typical giant star, no longer occurs, signifying that the stellar material is essentially exhausted in the sidereal universe we know; or (3) that the part of space where the phenomenon now occurs is remote from the region we ordinarily observe. Or stated more briefly we may suppose that the (1) *frequency*, (2) *epoch*, or (3) *place* of star-birth makes difficult or impossible our observation of the pre-giant stages.

The photographic observation of the magnitudes of the variables in Orion is very difficult because of the irregularity of the nebulosity and the uncertainties associated with the photographic study at Mount Wilson of southern objects in the winter season. Whether definite periodicity obtains for any of the variables has not yet been determined. Some of the stars previously suspected of variability may owe their apparent variations entirely to photographic phenomena; others at one time definitely variable now appear constant. The results so far derived for thirty variable stars near the

[1] The records of some globular clusters, and probably of the solar neighborhood as well, are sufficiently complete to show that such antecedents are not present as normal stars.

trapezium are mainly negative: (1) the variables do not belong to the cluster-type; (2) they are not blue (apparently they are mainly red, but the nebulosity introduces systematic error of undetermined amount into measures of color); (3) they do not appear to show regularity, or great range, or close similarity to each other in color or range; (4) they are, of course, not undergoing a secular increase of brightness apparent within this short interval of time; (5) the variables as well as other faint stars are concentrated in the central part of the nebula; (6) in the dense nebulosity the light of very few faint stars appears to be actually constant—perhaps a spurious photographic effect.

It seems impossible to say definitely as yet whether the variables are really associated with the nebula-group of bright stars and undergo intrinsic variations of light or are for the most part at a greater distance than the Orion stars and owe their variations to occultations by nebular matter. Most of the evidence, however, supports the view that the variables are typical dwarf stars within the nebula[1], deriving their irregular light-variations from contact with the irregular nebulosity, which recent spectroscopic work has shown to be moving differentially. Some strong points favoring this view may be inferred from the preceding paragraph, and together with some possible objections they will be more fully discussed when a detailed report is made on the magnitudes and colors. The similar, commonly-accepted hypothesis of nebular friction seems to account satisfactorily for the novae, where a much greater range of variation is involved.

L. *The most distant naked-eye star.*—The adopted lower limit of the parallax, $\pi = 0.''001$, of a hypothetical most distant naked-eye star depends upon the fairly safe assumption that the difference between apparent and absolute brightness, $m - M$, does not exceed ten magnitudes; that is, we assume that no first-magnitude star is brighter absolutely than -9, that no fifth-magnitude star is brighter absolutely than -5. The study of the giants in clusters, Kapteyn's work on B-type stars, and the results of direct measures of parallax support this assumption. The most relevant contribu-

[1] Recent studies of proper motion by van Maanen also strongly support this interpretation.

tion to this question, however, is the very important statistical discussion by Dyson of the proper motions of one-sixteenth of all the stars brighter than the ninth magnitude.[1]   He finds that brighter than the sixth magnitude there are in the whole sky only $15 \times 16 = 240$ stars more distant than 200 parsecs.   The extreme limit[2] of 260 parsecs, to which naked-eye stars extend according to Dyson's formula, is only one-fourth of the limit assumed for the present illustration.   We may note, however, that if a naked-eye Cepheid variable fainter than the fifth apparent magnitude should be found with period in excess of 32 days, its parallax would be somewhat smaller than the lower limit adopted above.

M. *Charlier's "Galaxy of B Stars".*—A discussion of the distribution in space of all B-type stars in the Harvard catalogues has been made by Charlier,[3] who finds that they form a large cluster, the center of which is nearly 100 parsecs distant from the sun.   As practically all the stars of all spectral types for which we know the position in space are within the bounds of this B-type cluster, it is chosen, in this comparison with the system of globular clusters, to represent the stellar system as ordinarily conceived.

N. *The eccentric position of the solar system.*—In the seventh paper it has been noted that the adopted distance to the center of the system of globular clusters is tentative, but probably of the correct order of magnitude.

Confirming Charlier's determination, either of the general direction or of the amount of the sun's displacement from the center of the local aggregation of stars, we have the results of Russell and Shapley on eclipsing binaries and Cepheids, of Walkey on 30,000 stars of the Harvard catalogues, and of Strömberg on second-type stars of known parallax and radial velocity.

<div align="center">SUMMARY</div>

This paper contains a tabular and diagrammatic comparison of various sidereal distances.   In addition to the material already available from the study of clusters and variables and from

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[1] *Monthly Notices*, **77**, 212, 1917.

[2] Dyson notes that the limit is too small; *ibid.*, p. 217.

[3] *Meddelanden från Lunds Astronomiska Observatorium*, Series 2, No. 14, 1916.

the results of other investigators, a considerable amount of new observational and computational work has been necessary for the discussion. The following statement summarizes the more important results, some of which are not specifically discussed in the text of the paper.

1. The most distant globular cluster now known, N.G.C. 7006, appears to differ from much nearer systems only in the matter of distance. In general appearance and in the relation of size to brightness it conforms with typical globular clusters; and in phenomena of color and the frequency of red giant stars it is very similar to Messier 3 and 13 (Table III).

2. The similarity in the frequency of colors for near and distant clusters shows that the selective scattering of light in space, if acting uniformly, affects the color-indices of stars by less than two-millionths of a magnitude for each parsec of distance. With any reasonable assumption as to the dependence of light-scattering on stellar concentration, interstellar media appear unimportant in their effect on the colors of stars brighter than the fifteenth magnitude.

3. The parallax of N.G.C. 7006 is $0''.000015$ on the basis of diameter measures, $0''.000014$ according to measures of photographic magnitude, and $0''.000016$ if the mean absolute photo-visual magnitude of its brightest stars be assumed equivalent to the corresponding means for Messier 3 and 13.

4. Counts of stars on photographs of the edges of globular clusters show that faint stars as well as the typical variables are widely dispersed. Probably the diameter of every typical globular cluster exceeds twenty million astronomical units.

5. As far from the center as $15'$, corresponding to a linear distance of about 65 parsecs, the elongation of Messier 15 is found to be in general agreement with the results for the central regions, both as to direction and amount.

6. The cluster N.G.C. 4147, which, of all known, is by far the most distant from the galactic plane, may differ considerably from typical globular systems in frequency of giant stars and perhaps in linear extent. A revision of the photographic magnitudes in this

cluster alters the previously adopted mean of the "25 brightest" stars by only five-hundredths of a magnitude.

7. A comparison of the direct and hypothetical parallaxes of seven eclipsing binaries shows an average difference of $\pm 0.''01$; the systematic difference is inappreciable.

8. Most if not all of the variable stars in the Orion nebula appear to be irregular in period and range; the color-indices of thirty situated in the denser nebulosity are large and positive. That the variables are actually associated with the nebula and therefore of faint absolute magnitude is not yet definitely proved.

MOUNT WILSON SOLAR OBSERVATORY
January 1918

ON THE GENERAL AURORAL ILLUMINATION OF THE SKY AND THE WAVE-LENGTH OF THE CHIEF AURORA LINE

By V. M. SLIPHER

Nature presents no sight so beautiful and wonderful as a brilliant display of the aurora. Records show that the aurora borealis has been observed since ancient times, and yet today it is not without mystery for many and is scientifically the least understood optical phenomenon of the earth. Quite naturally the spectrum of the aurora was studied by a wide circle of investigators, following the application of the spectroscope to astronomy. A bibliography of this spectroscopic work[1] alone would include upward of a hundred references and such names, well-known to astronomical literature, as Ångström, Young, Struve, Zöllner, Smyth, Vogel, Cornu, Holden, Tacchini, Secchi, Rowland, Copeland, Lockyer, Gyllenskiold, Huggins, Schuster, Pickering, Campbell, etc.

These early observations, made visually of course, revealed an interesting spectrum and established its general features. The observations could not be conducted deliberately with specially adjusted instruments and methods, on account of the character of the phenomena. Besides, the limited sensitiveness of the human eye left unexplored the more refrangible parts of the spectrum, and hence the complete investigation of the aurora spectrum depends upon the photographic method.

Professor Störmer's[2] very extensive observational and theoretical investigations into the nature of the aurora, and the late Professor

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[1] See Kayser, *Handbuch der Spectroscopie*, **5**, 47; and Frost-Scheiner, *Astronomical Spectroscopy*, p. 326.

[2] "Trajectories of Electric Corpuscles Applied to the Aurora Borealis and to Magnetic Disturbance," *Archiv for Mathematik og Naturvidenskab*, **28**, No. 2, 1906; see also *Archives des Sciences physiques et naturelles* (Genève), **24**, 5, 113, 221, 317, 1907, and **32**, 1911–12; and "Bericht über eine Expedition nach Bossekop zwecks photographischer Aufnamen und Höhenmessungen von Nordlichtern," *Videnskabs-Selskabets Skrifter, I, Math.-Naturv. Klasse*, 1911, No. 17, etc.

Birkeland's[1] vast work on polar magnetic storms and the related aurora, have added enormously to what we know in this field. Yet during this period our knowledge of the spectrum of the aurora has not been advanced proportionally, as it has hardly received its proper share of attention.

During the last few years I have done a little in the way of spectrographic observations which I shall give in this paper. These observations bear upon (1) the persistency of general auroral illumination of the sky, which is in continuation of the work briefly presented in *Lowell Observatory Bulletin*, No. 76, and (2) the wavelength of the chief aurora line in the yellow-green of the spectrum. A thorough investigation of the spectrum of the aurora can be done under conditions so much more advantageous at some northern station where brilliant displays of the aurora are frequent that undertaking it here is not considered.

Early in June, 1915, I recognized a faint line in the yellow region. This was on a negative which I had made, with an exposure of several nights, for the spectrum of the Milky Way, although the Seed 30 plate employed possessed only the ordinary emulsion, which is but slightly sensitive to the yellow of the spectrum. Hence the line in question must have been of pretty high equivalent brightness to have been recorded by the plate. I then undertook another spectrogram of the Milky Way, using a Cramer Isochromatic plate, the sensitiveness of which should easily record the line in question, suspected of being the aurora line, if of anything like the brightness indicated on the previous plate. However, this plate failed of its purpose in a singular manner. Its exposure, only partially completed, was continuing on the night of June 16, when there appeared that exceptional auroral display which was brilliant even at this low latitude (35°12'), and was the first aurora observed here in the history of the Observatory. Although the instrument was pointed toward the south, the light of the aurora of course got

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[1] *The Norwegian Aurora Polaris Expedition 1902–1903* (Christiania, 1913); "Expédition norvégienne de 1899–1900 pour l'étude des Aurores boréales, etc.," *Videnskabs-Selskabets Skrifter, 1901;* and *Archives des sciences phys. et nat.* (4), **1,** 512, 1896, and "Recherches sur les taches du soleil et leur origine," *Videnskabs-Selskabets Skrifter* (Christiania), pp. 2 and 167, 1899.

to the plate and strongly superposed itself upon the spectrum of the Milky Way and spoiled the plate for its intended purpose.

Since that time many spectrograms have been secured of the night sky to see whether it is always possible to record the chief auroral line and in that way definitely to recognize the presence of faint general auroral illumination of the night sky. In this work a small spectrograph of very high light-power (camera lens having speed $F/1.9$) has been employed, pointed directly to the region of the sky to be investigated, and generally left stationary during the exposure. In some instances an image-forming lens was placed before the slit. Recently, and especially for the long exposures for determinations of wave-length, the spectrograph has been directed upon the northern sky from the window of a basement room. Cramer Isochromatic plates have regularly been used, as they have a high sensitiveness for the yellow-green region of the spectrum, including the chief aurora line. In general each exposure has been continued through one night, although a number of plates were made of two exposures side by side for comparison of two different parts of the sky. In such cases the exposures were each for only one-half of the night. The presence of the moon does not seriously interfere with these observations, as the aurora line can be clearly seen, superposed upon the continuous spectrum of moonlight.

In the past three and one-half years something like one hundred spectrograms have been made of the night sky, and every one of these has recorded the chief aurora line. Thus during this period of time auroral illumination of the sky has been found to be present on every night that an exposure has been made for detecting it. The spectrograph therefore gives direct evidence of the existence of a permanent aurora.

The observations indicate an increase in the intensity of the aurora light as the zenith distance is increased. Also it is more intense in the sunrise and sunset parts of the sky than elsewhere. It is present in the southern as well as the northern sky, but seemingly less intense in the north than in the east and west. It is possible, however, that dawn and twilight may have influenced some of the plates, as a slight exposure of continuous spectrum of

the sky would tend to strengthen the image of the aurora line. These observations were not made with great care in such respects, as they were not intended for the purpose of studying the variation of the light in different parts of the sky, although the value of observations carried out for quantitative results in that direction has been appreciated.

The close dependence of displays of aurora upon sun-spot activity, which for some time has been well established, suggests that there are variations in the intensity of this permanent, general, auroral illumination of the sky. Thus there is good reason to expect less general light of the aurora in the sky during the time of sun-spot minima than during sun-spot maxima.

To realize that it is astronomically of vital importance to know whether or not there exists a general, permanent, auroral illumination of the sky, it is only necessary to refer to the work that has been done in attempting to measure the brightness of the night sky in determining the total light of all the stars.[1] Newcomb, who seems to have been the first to take up this work, presents the needs and importance of investigation in this field in the following words:

> The total amount of light received from all the stars may serve as a control on theories of the structure of the universe, because the amount of light resulting from any theory should agree with the observed amount. It is also a quantity which we must regard as remaining constant from age to age. It seems possible to determine, not only its integral value for the whole sky, but its value separately in each region of the sky. For these reasons it must be considered as among the most important fundamental constants of astrophysics.

So much for the need of reliable measures of the brightness of the starlit sky and the total light of all the stars. That serious difficulties have been encountered and divergent results obtained in carrying out the necessary observations is evidenced by the following quotations from the recent paper on the subject by

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[1] Newcomb, "A Rude Attempt to Determine the Total Light of All the Stars," *Astrophysical Journal,* **14,** 297, 1901. Burns, "The Total Light of All the Stars," *ibid.,* **16,** 166, 1902. See also *The Observatory,* **33,** Nos. 420 and 421, 1910. Townley, *Publications of The Astronomical Society of the Pacific,* **15,** 13, 1903. Yntema, "On the Brightness of the Sky and Total Amount of Starlight," *Publications of the Astronomical Laboratory at Groningen,* No. 22, 1909. Fabry, "The Intrinsic Brightness of the Starlit Sky," *Astrophysical Journal,* **31,** 394, 1910.

Professor Charles Fabry (*loc. cit.*, p. 399), in which he concludes his discussion of his observations by saying:

> Upon the whole, therefore, the data actually obtained on the number of stars are very far from being in accord with the results of measures of intrinsic brightness. Is the disagreement a result only of inaccuracy of the measures and of the statistical data? That is not certain. If it were proved that the total intensity of the sky exceeds considerably the sum of the intensities of the observable stars, one could advance two hypotheses: either that there exists an immense number of stars too faint to be observed with our instruments, or that there exists throughout the sky a sort of continuous nebulosity giving a uniform brightness.

As an appendix to his paper, added later, he comments upon the extensive similar investigation of Yntema, thus:

> Very recently, Yntema has made a great many visual measures. The most important conclusion from his observations is that a great part of the light of the sky is of terrestrial origin. This result seems to be peculiar to the conditions under which Yntema has observed. No other observer has found, from one date to another, such large variations as those observed by him. The brightness of a square degree in the region of the celestial pole would equal 0.19 that of a star of magnitude 1, a result about four times as large as those found by other observers. . . . . The only conclusion to be drawn from these great discordances is that measures made in different epochs and in different places would be very useful.

Hence these spectrographic tests on a general illumination of the sky by aurora light serve to establish an important fact. While this disturbing factor in these important photometric researches has been photometrically a very troublesome one, it has yielded readily to spectrographic analysis. The case offers a good example of the directness and definiteness of solution sometimes given by the spectrograph to astrophysical problems.

These spectrographic results suggest the cause for the discrepancies in the measures of the brightness of the sky by the different observers referred to above. For example, it seems probable that Yntema, observing at a more northern station, encountered more intense auroral illumination of the sky than did the other observers, who were farther south. This could account for the greater brightness that he found for the polar region, and it is possible that the variation he found from date to date was due to occasional weak auroral displays not recognizable as such.

Newcomb, Burns, and Townley observed at a time nearly coinciding with a sun-spot minimum and Yntema nearer spot maximum than did Fabry. This would affect the observations if, as is to be expected, the intensity of the persistent aurora light is, like the aurora displays, greater during sun-spot maxima than during minima. Here it is well to call attention to the fact that Fabry observed photographically, and consequently his results should have been less affected by aurora light than if they had been obtained visually, since the yellow-green radiation of the aurora would affect the eye much, but the ordinary plate scarcely at all. However this may be, it is unfortunately not possible to correct these extensive observations on the total light of all the stars for the disturbing aurora light; but it seems clear that such observations in future will need to be made with care as to the presence of aurora light in the sky. Spectroscopic tests of the sky could be made to decide whether or not the night is a suitable one for the purpose, or as good as any to be had. Besides, the employment of a color-screen so adjusted as to absorb the auroral radiations is to be considered essential. To this end more should be known of the spectrum of aurora light, but a screen cutting out the chief line in the yellow would doubtless materially improve visual observations of the brightness of the light of all the stars.

The finding of the spectrograph substantiates Yntema's conclusion that "the light of the sky at night is composed of two parts, one reaching us directly from the stars, the other resulting from processes in the atmosphere. The latter termed 'earthlight,' is only partly due to diffused starlight. It seems probable that the rest, wholly or in part, is due to a permanent aurora." At that time Yntema was strengthened in his conclusion by reports of several observers[1] who had seen the chief aurora line in the spectrum of the sky on nights when they did not recognize any of the phenomena of an auroral display.

[1] Ångström, *Die Spectralanalyse in einer Reihe von sechs Vorlesungen*, Braunschweig, 1870, p. 180. Vogel, *Astronomische Nachrichten*, **79**, 327, 1872. Campbell, *Astrophysical Journal*, **2**, 162, 1895; also *Lick Observatory Bulletin*, **5**, 46–47, 1908, and more recently *Publications of the Astronomical Society of the Pacific*, **29**, 218, 1917; Wiechert, *Physikalische Zeitschrift*, **3**, 366, 1902; and *Meteorologische Zeitschrift*, **19**, 315, 1902.

This subject invites much further spectrographic study with a view to more quantitative results. Simultaneous observations with duplicate instrumental means at two stations separated considerably in latitude should secure comparable material of the highest value in itself and in its bearing on other problems; and it is hoped that some observer stationed farther north will become sufficiently interested to take up the work of investigating the spectrum (which should not be difficult to one favorably located) and particularly in joining in a co-operative plan, possibly with this Observatory, in the further study of the general auroral illumination of the night sky.

WAVE-LENGTH OF THE CHIEF AURORA LINE

In following up the measurement of one of the earlier of the plates taken with low dispersion, which had indicated a longer wave-length for the chief line than the commonly accepted value of λ 5571, I measured several additional plates. These resulted in a considerably longer wave-length. While the scale of the plates was small, their individual results agreed satisfactorily, and the deviation from the old value seemed too great and persistent to be brushed aside as errors of observation.

It thus appeared desirable to determine the wave-length with more accuracy, and I adjusted a powerful three-prism spectrograph, with a 15-inch camera, for the desired region of the spectrum and made some plates with this high dispersion. The exposures were continued over many nights, the last one running considerably over one hundred hours. The instrument was in a basement room, of uniform temperature, and directed through a window to the northern sky a little way below and to the east of the pole. Three of these plates taken with higher dispersion were secured and each measured twice, with the results:

$$\text{I} \dots \dots \dots \dots \left\{ \begin{matrix} 5578.06 \\ 5577.95 \end{matrix} \right\} 5578.01$$

$$\text{II} \dots \dots \dots \dots \left\{ \begin{matrix} 5578.11 \\ 5578.00 \end{matrix} \right\} 5578.05$$

$$\text{III} \dots \dots \dots \dots \left\{ \begin{matrix} 5577.99 \\ 5578.17 \end{matrix} \right\} 5578.08$$

Final mean $= 5578.05$

The sky spectrum served for comparison on these plates and was exposed briefly on a number of days during the period of the exposure to the aurora.*

The wave-length yielded by these high-dispersion plates is slightly greater than that shown by the small-scale ones, and greater by fully seven units than the usually accepted value. So large a deviation from the old value is very surprising and by present standards intolerable. I can find nothing wrong with the new value; the employment of the solar comparison spectrum precludes misidentification of the reference lines or their wave-lengths. The high-scale spectrograms show at a glance that the strong solar line λ 5573.075 falls well to the violet side of the image of the aurora line, the wave-length of which, hence, obviously cannot be anything like λ 5571, the previously accepted value. Spurious displacements in these spectrograms must, of course, be inappreciable in comparison, and we must attribute the discrepancy to the old visual observations, for we cannot assume a shifting aurora line. In this connection we should not lose sight of the fact that the visual observations were often made under very unfavorable conditions that permitted only estimate of the line's position or wave-length. There seems no escaping the conclusion from the high-scale spectograms that the wave-length of the line is substantially λ 5578.05.

Photographic observations of the spectrum of the aurora since 1900, by Paulsen,[1] Sykora,[2] Westman,[3] and Vegard,[4] included

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* EDITORIAL NOTE.—The author has sent me a lantern slide of the spectrum of the aurora and sky which shows the green line very strongly, while the solar lines are too faint for successful reproduction. At his request I am glad to state that it is perfectly evident that the green line falls at a point of greater wave-length than the solar line λ 5573, in fact nearly 1 mm toward the red from that line on the scale of the slide.   E. B. F.

[1] "Sur le spectre des aurores polaires," *Comptes rendus*, **130**, 655, 1900; *Rapp. Congr. Internat. de Physique* (Paris), **3**, 438–52, 1900; and *Rep. Brit. Asso.*, pp. 575–78, 1903.

[2] "Die Wellenlängen der photographisch erhaltenen Linien des Nordlicht-spectrums," *Astronomische Nachrichten*, **156**, 326, 1901.

[3] *Aurores boréales. Mission scientifique pour la mesure d'un arc de méridian au Spitzberg* (Stockholm), **2**, 1904.

[4] "Photographische Aufnahmen des Nordlichtspectrums mit einem Spectrographen von grosser Dispersion," *Physikalische Zeitschrift*, **14**, 677–81, 1913.

determinations of the chief line, but these do not incline strongly toward the value I have found. Values obtained visually by Vegard with a direct-vision spectroscope are: λ 5576.9, using helium reference lines, and λ 5573.7, referred to hydrogen lines. But his photographic value fell back to λ 5571.3, and he suggested λ 5572.5 as a mean result from his observations. Westman got λ 5572.6, Sykora λ 5570, and Paulsen's value seems indefinite, although I have not been able to consult his original paper. These observations, even those of Vegard, who apparently observed under unusually favorable circumstances, appear to have left the wave-length rather uncertain according to present-day standards.

The new value of the wave-length resulting from my observations has not yet led to the identification of the chemical substance involved, and nothing promising falls near it. In this regard the old value offered more encouragement, as it chanced to come near a strong krypton line.[1]

Reference was made early in this paper to a spectrogram of the Milky Way which was exposing on the night of June 16, 1915, and so recorded the spectrum of the aurora of that night. The spectrograph was unfortunately directed toward the south and adjusted with a wide slit for the continuous spectrum of the Milky Way. Thus the conditions were unfavorable for a good spectrum of the aurora because it was, of course, blended with that of the Milky Way, although the latter was not very strong. It may be of interest, however, here to describe briefly the aurora spectrum. On this plate the chief aurora line is exceedingly intense, and a line near λ 3916 is fairly strong, while weaker ones are doubtless present near $\lambda\lambda$ 4277, 4180, 4450, and 3740. These wave-lengths are only approximate. Certainly the lines λ 3916 and λ 4277 have been recorded before, and very possibly the others, too.

In conclusion I wish to call attention to the evident need for a thorough investigation of the auroral spectrum and to emphasize the fact that, where brilliant auroras are frequent, valuable results should not be laborious of realization with a suitable spectrograph, i.e., one with moderately high angular dispersion and a fairly short camera.

[1] C. Runge, "On the Spectrum of the Aurora," *Astrophysical Journal*, **18**, 381, 1903.

Note added April 5, 1919:.

Professor Frost has kindly called my attention to an extensive paper by J. Stark on the identification of the lines of the aurora spectrum, under the title: "Das Nordlichtspektrum ein Spektrum positiver Strahlen" (*Annalen der Physik*, No. 24, 598, 1917). It is to be noted that Stark, like Vegard (see previous reference), finds very close correspondence between the auroral spectrum and that of nitrogen, except in the case of the chief aurora line— and this line Stark regarded as very probably due to the pair of nitrogen lines 5560–5565 A. However, the new wave-length, 5578.05 A, for this line makes such an identification quite inadmissible, and implies a separate—non-nitrogen—origin for this line. Stark's work emphasizes still more the need for accurate knowledge of the other lines of the auroral spectrum, and it is to be hoped that this information will soon be available for such laboratory studies as Stark's on the origin of the features of the spectrum. These studies are of the highest importance in completing our knowledge of the aurora and in disclosing the nature of the upper air.

LOWELL OBSERVATORY, FLAGSTAFF, ARIZ.
March 3, 1919

SPECTRA AND ATOMIC NUMBERS OF THE ELEMENTS

By J. E. PAULSON

In the case of all spectra which exhibit series, it has long been known that there exists a certain relation between the frequency-difference of certain lines and the atomic weight of the substance. For elements belonging to the same group in the periodic system, the frequency-difference between the lines belonging to the first doublet or triplet of the principal series is approximately proportional to the square of the atomic mass of the element. As is known, the same difference exists between all the doublets or triplets of the subordinate series. In Table I are shown the values which Rydberg[1] has computed for $\dfrac{10^3 \nu}{P^2}$, where ν indicates the frequency-difference and P the atomic weight.

<div align="center">TABLE I</div>

	P	ν	$\dfrac{10^3\nu}{P^2}$		P	ν_1	ν_2	$\dfrac{10^3\nu_1}{P^2}$	$\dfrac{10^3\nu_2}{P^2}$
Li...	7.03	0?	0?	Mg.	24.38	40.91	19.85	68.8	33.4
Na..	23.06	17.19	32.3	Ca .	40.00	105.82	52.16	66.1	32.6
K...	39.14	57.85	37.8	Sr..	87.52	394.22	186.83	51.5	24.9
Rb..	85.44	235.98	32.3	Ba .	137.04	878.5	370.4	46.8	19.7
Cs...	132.88	553.87	31.6						
Cu ..	63.44	248.54	61.8	Zn .	65.38	388.97	189.82	91.0	44.4
Ag...	107.94	920.48	79.0	Cd .	112.08	1170.76	542.09	93.2	43.1
Au ..	197.25	3815.40	98.1	Hg .	200.36	4631.17	1767.09	115.4	44.0
Al...	27.08	112.02	152.8	O ..	16.00	3.70	2.08	14.5	8.1
Ga ..	69.9	823.6	168.6	S...	32.06	18.15	11.13	17.7	10.8
In...	113.4	2212.54	172.1	Se..	79.07	103.7	44.07	16.6	6.6
Tb ..	204.15	7792.63	187.0						

As will be seen from the table, this proportionality between ν and P^2 is not strictly constant. Since the frequency-difference can be expressed only approximately by use of the second power of the atomic weight, one naturally sets it proportional to an

[1] J. R. Rydberg, *Rapport au Congrès international de Physique*, Paris, 1900.

arbitrary power of the atomic weight, this power being different for each related group in the periodic system of elements. This is the method which has been used by Runge and Precht.[1] These authors represent the connection between ν and P in a system of co-ordinates, in which the variables are $\log \nu$ and $\log P$; and they find that the curves thus obtained are straight lines. On this basis they then proceed to compute the atomic weight of radium, a quantity at that time imperfectly known. But the rectilinearity of these curves is only, however, approximate, as one can easily see from a large-scale drawing.

Since no other relation between the spectra of elements and their other properties has yet been discovered, it has seemed to me worth while to study the question further. Since the atomic weight is surely complex in its nature and does not definitely determine the position of its element in the periodic system, it has seemed clear to me that the atomic weight is not the proper variable in which to express the properties of the elements. To start from the Atomic Numbers which are whole numbers and which definitely locate the elements in the periodic system would appear to be a better procedure. In what follows I shall employ the system proposed by Rydberg.[2] But in some cases it is quite possible that other values would have fitted in better. Rydberg's system is shown in Table II.

TABLE II

V	o	I	II	III	IV	V	VI	VII	VIII	—
G¹ ..	E(o) -(2)	H(1) -(3)									
G² ..	He(4) Ne(12)	Li(5) Na(13)	Be(6) Mg(14)	B(7) Al(15)	C(8) Si(16)	N(9) P(17)	O(10) S(18)	F(11) Cl(19)		
G³ ..	Ar(20) Ni(30) Kr(38) Pd(48)	K(21) Cu(31) Rb(39) Ag(49)	Ca(22) Zn(32) Sr(40) Cd(50)	Sc(23) Ga(33) Y(41) In(51)	Ti(24) Ge(34) Zr(42) Sn(52)	V(25) As(35) Nb(43) Sb(53)	Cr(26) Se(36) Mo(44) Te(54)	Mn(27) Br(37) -(45) I(55)	Fe(28) Ru(46)	Co(29) Rh(47)
G⁴ ..	X(56) Sm(64) Pt(80) Nt(88)	Cs(57) Eu(65) Au(81) -(89)	Ba(58) Gd(66) Yb(72) Hg(82) Ra(90)	La(59) Tb(67) Lu(73) Tl(83) -(91)	Ce(60) Dy(68) -(74) Pb(84) Th(92)	Pr(61) Ho(69) Ta(75) Bi(85) -(93)	Nd(62) Er(70) W(76) -(86) U(94)	-(63) Tu(71) -(77) -(87)	Os(78)	Ir(79)

My attempt has been to discover that function of the Atomic Numbers which will best represent the observed values of the

[1] *Physikalische Zeitschrift*, 4, 285, 1903.   [2] *J. Ch. Phys.*, 12, No. 5, 1914.

frequency-difference ν. The first expression which suggests itself is that obtained by substituting the Atomic Number for the atomic weight, which at once leads to the formula

$$\nu = [A \log N + B],^{1}$$

where A and B are constants. As a matter of fact, this equation represents the observed values generally just as well as, and in several cases better than, the corresponding equation using atomic weights

$$\nu = [A \log P + B].$$

The following formula, however, will give still better agreement, namely

$$\nu = [A \log (N+n) + B],$$

where n is a whole number, which may be positive or negative, and which is generally small. I am quite convinced that if one were to change the formula involving atomic weights in a corresponding way, so as to read

$$\nu = [A \log (P+n) + B],$$

one would also secure better agreement. Since it is difficult to assign any physical meaning to such an expression, I have not examined it further.

The following gives the result of my investigation, and also a comparison with the values obtained by use of the atomic-weight formula. The constants A and B have in each case been computed by the method of least squares. The value of n was first determined graphically.

Group I:1.   Li, Na, K, Rb, Cs.
$$\nu_{N} = [2.055461 \log (N-3) - 0.819328]$$
$$\nu_{P} = [1.953599 \log P - 1.393596]$$

TABLE III

	N	P	ν	ν_{N}	Diff.	ν_{P}	Diff.
Li......	5	6.94	0?*	(0.63)	....	(1.78)	....
Na......	13	23.00	17.21	17.22	—0.01	18.48	− 1.27
K.......	21	39.10	57.90	57.66	+0.24	52.10	+ 5.80
Rb......	39	85.45	237.71	239.66	−1.95	239.99	− 2.28
Cs......	57	132.81	554.10	551.50	+2.60	568.00	−13.90

* Not included in the calculation.

1 This symbol [ ] denotes the antilogarithm.

The computed value for lithium is, of course, too great and for the principal line λ 6708 would correspond to a difference of wavelength amounting to 0.28 A.

Group I:2. Cu, Ag, Eu, Au.

$$\nu_N = [2.786693 \log (N-1) - 1.721416]$$
$$\nu_P = [2.413119 \log P - 1.951540]$$

TABLE IV

	N	P	ν	ν_N	Diff.	ν_P	Diff.
Cu..	31	63.57	248.13	248.24	−0.11	251.15	−3.02
Ag..	49	107.88	920.56	919.78	+0.78	899.89	+20.67
Eu..	65	152.0	....	(2050.47)	....	....	....
Au..	81	197.2	3817.11	3818.67	−1.56	3857.84	−40.73

For gold I have assumed the fundamental lines to be $\lambda\lambda$ 2676.06 and 2428.04, which yield values agreeing well with those computed. In the case of europium, no series have yet been found. Under the supposition that this element belongs to this group, I have computed the frequency-difference, ν, to be 2057.17. In a previous paper[1] I have listed some constant frequency-differences found in the europium spectrum, of which the most frequently recurring is 1669.71. Four doublets showing this difference involve eight of the strongest lines of this spectrum. It is not likely that this frequency-difference is identical with the one computed; and a second attempt to discover a frequency-difference agreeing better with the computed value has led to no favorable result. Possibly the discrepancy is due to a mistake in Rydberg's system.

Group II:1. Mg, Ca, Sr, Ba, Yb, Ra.

$$\nu_{1N} = [2.163129 \log N - 0.871542]$$
$$\nu_{2N} = [1.748748 \log (N-4) - 0.459734]$$

$$\nu_{1P} = [1.756001 \log P - 0.809218]$$
$$\nu_{2P} = [1.680803 \log P - 1.006520]$$

[1] *Astrophysical Journal*, **40**, 298, 1914.

TABLE V

	N	P	ν_1	ν_2	ν_{1N}	Diff.	ν_{2N}	Diff.	ν_{1P}	Diff.	ν_{2P}	Diff.
Be...	6	9.1	....	....	(6.48)	....	(1.17)	....	....	....	....	....
Mg...	14	24.32	40.92	19.89	40.52	+0.40	19.45	+0.44	42.12	−1.20	21.04	− 1.15
Ca...	22	40.07	105.99	52.11	107.72	−1.73	54.38	−2.27	101.24	+4.75	48.70	+ 3.41
Sr....	40	87.63	304.44	187.05	392.57	+1.87	182.74	+4.31	400.02	−5.58	181.42	+ 5.63
Ba...	58	137.37	878.4	370.3	876.96	+1.44	371.35	−1.05	880.89	+2.40	386.27	−15.97
Yb...	72	172.0	....	....	(1399.84)	....	(555.73)	....	....	....	....	....
Ra...	90	226.4	....	....	(2268.33)	....	(837.95)	....	....	....	....	....

No triplets are known which correspond to the computed values for the three elements, Ba, Yb, and Ra.

Group II:2.   Zn, Cd, Gd, Hg.

$$\nu_{1N}=[3.522017 \log (N+17)-3.362998]$$
$$\nu_{2N}=[2.466934 \log (N+2)-1.499658]$$

$$\nu_{1P}=[2.220238 \log P-1.458622]$$
$$\nu_{2P}=[1.998697 \log P-1.357823]$$

TABLE VI

	N	P	ν_1	ν_2	ν_{1N}	Diff.	ν_{2N}	Diff.	ν_{1P}	Diff.	ν_{2P}	Diff.
Zn ...	32	65.37	388.91	189.78	388.96	−0.05	189.85	−0.07	377.02	+ 11.89	188.17	+ 1.61
Cd...	50	112.40	1171.05	541.86	1170.76	+0.29	541.51	+0.35	1243.27	− 72.22	550.85	− 8.99
Gd...	66	157.3	....	....	(2489.01)	....	(1049.59)	....	....	....	....	....
Hg...	82	200.6	4630.31	1767.19	4630.86	−0.55	1767.71	−0.52	4498.84	+131.47	1753.23	+13.96

Concerning ν_{1N}, graphical construction shows that an abnormally high value must be given to n, namely, $n=17$. This may appear questionable. The agreement is very good, however. The formula for ν_{1P}, on the other hand, shows great discrepancies. In case of the gadolinium spectrum, I have previously described[1] a connected system of lines of the type usually occurring in those spectra which are devoid of series. It is therefore doubtful whether this element belongs to the group. I have not found any triplet which corresponds with the predicted values.

Group III.   B, Al, Ga, In, Tb, Tl.

$$\nu_N=[2.712737 \log (N+3)-1.355479]$$
$$\nu_P=[2.094583 \log P-0.955935]$$

[1] *Physikalische Zeitschrift*, 16, 1915.

TABLE VII

	N	P	ν	ν_N	Diff.	ν_p	Diff.
B......	7	11.0	....	(22.76)	....	....	....
Al.....	15	27.10	112.07	112.14	− 0.07	111.06	+ 1.01
Ga.....	33	69.9	823.6*	(735.12)	....	....	....
In.....	51	114.8	2212.63	2208.26	+ 4.37	2284.46	− 71.83
Tb....	67	159.2	....	(4464.65)	....	....	....
Tl.....	83	204.0	7792.95	7803.78	−10.83	7616.88	+176.07

* Not sure and not included in the calculation.

The principal lines in the spectrum of boron, λλ 2497.80 and 2496.84, have a frequency-difference of 15.40, which possibly is identical with the computed one. In the Tb spectrum, no series have yet been found.

Group IV.   O, S, Se, Te, Er, −(86)

$$\nu_{1N}=[2.208775 \log (N-3)-1.340342]$$
$$\nu_{2N}=[1.665132 \log (N-4)-0.855511]$$

$$\nu_{1P}=[2.130683 \log P-2.007606]$$
$$\nu_{2P}=[1.732346 \log P-1.613456]$$

TABLE VIII

	N	P	ν_1	ν_2	ν_{1N}	Diff.	ν_{2N}	Diff.	ν_{1P}	Diff.	ν_{2P}	Diff.
O......	10	16.00	3.38	2.76	3.36	+0.02	2.76	0.00	3.61	−0.23	2.97	−0.21
S.......	18	32.07	17.90	11.26	18.09	−0.19	11.30	−0.04	15.90	+2.00	9.90	+1.36
Se......	36	79.2	103.66	44.82	103.29	+0.45	44.75	+0.07	109.14	−5.58	47.40	−2.58
Te.....	54	127.5	....	....	(269.96)	....	(94.08)	....	....	....	....	....
Er.....	70	167.7	....	....	(493.23)	....	(149.37)	....	....	....	....	....
−(86)..	86	....	....	....	(791.54)	....	214.41	....	....	....	....	....

No series are known in the spectrum of either tellurium or erbium.

Umeå, Sweden
October 1918

CORRELATION BETWEEN THE COLOR-SCALES OF ONE AND OF TWO DIMENSIONS

By J. G. HAGEN, S.J.

In a former number of this Journal (**34,** 261, 1911) the writer gave the history and the definitions of the two color-scales: the two-dimensional, which is used exclusively in England; and the one-dimensional, generally applied on the Continent.

1. At that time no comparison based on observations was possible, and so an attempt was made to co-ordinate the two scales from a purely mathematical point of view. The result is shown in Table I. It need only be mentioned that B stands for blue and S for somber or dark, and that in the compound letters the left-hand symbol has the adjectival meaning, e.g., YW = yellowish white.

TABLE I

WHITE			YELLOW			ORANGE			RED		
BW	W	YW	WY	Y	OY	YO	O	RO	OR	R	SR
−1	0	1	2	3	4	5	6	7	8	9	10

To make this table a practical one that can be used as a transition from one scale to the other would require, strictly speaking, that each observer express his estimates both by letters and by numbers. As this can hardly be expected, it only remains to construct a mean table by collecting the estimates of different observers and comparing letters with numbers.

2. This can now be done, since the observations of Franks, on the one hand, and of Krüger and Osthoff on the other, will appear in the forthcoming publication, No. IX, of the Vatican Observatory, which concludes the third volume of Series II.

There are 3162 stars observed by Franks on the areal, and by Krüger and Osthoff on the linear, scale. The result of the comparison is represented in Table II. The single-letter symbols of

Franks were written on separate sheets, and the corresponding numbers of Krüger or Osthoff, or both, were then collected and combined into mean values. The letter *n* denotes the number of stars in each case. An exception was made for the symbol W, which was compared with Osthoff's numbers only, exclusive of Krüger's, because Krüger saw the white stars more yellowish.

TABLE II

Yellowish Colors			Orange Colors			Peculiar Colors		
Fr.	K.-O.	*n*	Fr.	K.-O.	*n*	Fr.	K.-O.	*n*
W	1.99	553	$\overline{OY}^1$	4.23	4	B^1	2.01	7
Y^1	3.09	799	OY^2	5.86	78	G^1	2.39	13
Y^2	4.96	653	OY^3	6.42	72	$\overline{YG}^1$	2.82	55
Y^3	5.88	493	O^1	3.30	15	$\overline{YG}^2$	3.57	3
			O^2	6.35	253	R^1	3.40	6
			O^3	6.70	137	$\overline{OR}^1$	3.35	2
			$\overline{OR}^3$	7.71	17	V^2	1.50	2
Total	....	2498	....	....	576	....	....	88

3. It now remains to examine the effect of saturation indicated by exponents in the two-dimensional scale. This question is of special interest, because it touches the radical difference between the two scales, at least from yellow as far as red.

Leaving out for the moment the peculiar colors, we collect the letter-symbols that correspond nearly to the same number, and combine these numbers into mean values. We thus obtain Table III. The second line of the table is marked normal, because in the linear scale the shadings of yellow are treated as normal steps or grades. It will be noticed that Franks has not estimated any star as purely red.[1]

A number of conclusions may be drawn from Table III:

a) The W-estimates of Franks coincide nearly with those of Potsdam. According to the *Generalkatalog*, p. xxi, the symbol W corresponds to the number 2.4 of Osthoff. This means that

[1] Apart from variables, the catalogues of K.-O. contain a few stars between the color-grades 8 and 9, e.g., K 844, 1079, O 2264.

Osthoff discerned the shadings of yellow more minutely than any other observer.

b) The normal colors of Franks for all the tones have the index 3. This fact is important, as it shows that the four degrees of saturation proposed by Smyth and retained generally are only theoretical, and that practically the normal shading is 3, which, by the way, is an improvement on the theory (see the writer's article quoted above, p. 272).

TABLE III

Krüger-Osthoff	2.0	3.2	4.6	5.9	6.4	6.7	7.7	—
Normal colors...	W	Y^1	Y^2	Y^3	$\overline{OY}^3$	O^3	$\overline{OR}^3$	R^3
Shifted colors...	....	O^1	$\overline{OY}^1$	$\overline{OY}^2$	O^2	....	....	....

c) Lowering the exponent shifts the letters from right to left, i.e., from red to white. Now the fact that the shifted symbols all contain orange, which is a tone and not a shading, teaches an important lesson: What the areal scale expresses as a shading is in the linear scale a different tone. To explain more in particular, O^2 is meant to be a pale orange; now a pale orange seems to be necessarily a yellowish orange and hence a tone different from orange. Again, $\overline{OY}^2$ is a pale orange yellow; what else can it be than a pure yellow i.e., a lower tone in the scale? Similarly, the symbols O^1 and $\overline{OY}^1$ are supposed to designate very faint tints of orange. Can the most experienced observer distinguish them from shadings of yellow? Krüger and Osthoff could not, nor can the writer.

It seems then that the symbols in the last line of Table III have only a theoretical meaning, like the exponent 4, and that practically the symbols that stand in the vertical columns of Table III are identical.

d) Comparing Tables I and III, we notice that the normal colors in the second line of Table III have a shorter range than the letter-symbols of Table I, both in form and in substance. In form, because they contain eight symbols against ten in Table I; and in substance, because the range from W to $\overline{OR}^3$ is 5.7 steps, while in the numerical scale there are 7.5 grades from W to $\frac{1}{2}$ (RO+OR).

The question whether a shorter scale is preferable or not is far less important than an attempt to establish a closer agreement between the color-scales. Two simple changes in the areal scale would make the correlation almost perfect. The first is that permutations be admitted in the compound letter-symbols; and the second that the exponents be replaced by the letters W and S, as in Table I. More detailed suggestions were proposed by the writer in the article quoted, p. 273.

e) Finally, as regards the peculiar colors of Table II, they lie outside the numeral scale and, in fact, could not be expressed in its digits. This circumstance forms a decided advantage of the letter-scale, although it cannot be called an essential deficiency of the number-scale. Both Krüger and Osthoff maintain that those peculiar colors, especially the tints of blue and green, are seen only in double stars, and that observations of this kind in single stars are always traceable to some error. The mean of the last column K.-O. in Table II is 2.73, i.e., on the eyes of Krüger and Osthoff those 88 stars of Franks made the average impression of a pale yellow. In whatever manner this question may be decided, let both scales, the literal and the numeral, exist side by side and supplement each other's defects.

One paramount advantage of the number-scale is asserting itself at the present time, when numerous observations of Nova Aquilae are being reduced and published, to which a color-correction is, or should be, applied for each observer. A linear formula like this,

$$\text{Mag.} = x + y \text{ Grade} + z \text{ Color,}$$

is usually sufficient. The unknown coefficients are obtained from the comparison-stars, for which the photometric magnitude, the scale of grades, and the color are supposed to be known. A solution by least squares will furnish the zero point x, the step value y, and the color-coefficient z.

Evidently a literal scale cannot lend itself to the reduction, unless it be transformed into numbers by some means like Table II.

VATICAN OBSERVATORY, ROME
February 1919

REVIEWS

Geschichte und Literatur der veränderlichen Sterne. Band I.
 G. Müller und E. Hartwig.

A free translation of the full title of this work is: "History and Litera-
ture of the Light-Changes of the Stars Recognized as Variable up to the
End of 1915, as well as a Catalog of the Elements of their Variations,"
edited under instructions from, and at the cost of, the Astronomische
Gesellschaft, by G. Müller and E. Hartwig (Leipzig, Poeschel and
Trepte, 1918. Vol. I).

The first catalogue of variable stars appeared in the *Philosophical
Transactions* for 1786, written by Pigott and containing "observations
and remarks" on 12 known and 38 suspected variables. The work
under review describes 1687 variables, of which 838 are found in the
first volume of xvi+401 folio pages. The stars are arranged in order
of right ascension and the hours 0 to 14 inclusive appear in this volume.
The second volume will contain the stars in the remaining hours, and
also a list of probably variable but as yet unconfirmed stars, mostly
found on the photographs taken at the Harvard College Observatory
and at Heidelberg. The third volume will have the catalogue of latest
elements of variation and a number of auxiliary tables, but no graphic
light-curves.

This great work was planned in 1901 when Chandler announced that
his series of catalogues of variables could no longer be continued. The
Gesellschaft appointed as a committee: Dunér, Müller, Oudemans, and
Hartwig. Kempf was added to the number after the deaths of Dunér
and Oudemans. The scope of the work grew during years of planning
till it finally included everything that could be classed as historical about
all the known variable stars. No wonder that the mere title is so ponder-
ous as to be even top-heavy, when the plan was so inclusive and the
contents were made to measure up to the plan.

This review must be limited mainly to the history of the undertaking,
which is described in 16 folio pages of introduction. A collection was
first made of all the known literature bearing on variables, and a card
catalogue was made by individual stars. This literature was examined

with great care by Müller, Boegehold, Hartwig, Zinner, Lehnert, Schulz, and Pračka. Efforts were made to collect as much unpublished material as possible, but the editors admit that many important series, especially from American observers, were not available to them. On the other hand, of the three sources considered the most valuable, the *Astronomische Nachrichten*, the *Astronomical Journal*, and the *Harvard Annals*, two are American.

After three years of labor the literature was assembled and the card catalogue brought up to date. Since the completion of the work as planned was evidently beyond the powers of the commission alone, co-workers were secured, including Beljawsky, Van Biesbroeck, Boegehold, Ebell, Fagerholm, Graff, Guthnick, Lehnert, Pračka, Rosenberg, and Zinner. The stars were divided among these co-workers, copies of the card catalogue being furnished them by Frau Müller, and the actual work of arranging the material for publication was begun. In the published work the reports on the individual stars are signed by the author's initials.

The commission felt obliged to suspend the rule requiring two witnesses to a star's variability before it was admitted to the catalogue, and included many stars vouched for by a single reputable observer, if the change observed visually amounted to half a magnitude; or, if found from photographs, if it changed a full magnitude. They speak of the difficulty of forming a judgment on account of the failure of the discoverer to publish his original comparisons. They bemoan the fact that many valuable series of observations remain so long unpublished; and, oddly enough, mention Hartwig, one of their own number, as an offender in this respect.

The important question of reform in the nomenclature of variables is discussed at length; with the final decision to adhere to the old system, with amendments to make it last for a decade or two at most, rather than to break boldly with tradition and inaugurate a lasting system.

A compromise of somewhat similar nature is made in the matter of color. Osthoff's visual scale is adopted and tables are given for converting to his standard the systems of Chandler, Innes, Krüger, Müller and Kempf, Nyland, Pračka, and Yendell. No mention is made of color-index or the ever-present changes in color with variation in light.

The spectral classification is taken from *Harvard Annals*, Vol. 56, No. 6, which is Mrs. Fleming's "Stars Having Peculiar Spectra."

Great care is taken in the matter of accurate positions, and authorities are quoted for each star. The statement is made that "precise

positions are valuable not only for certain identification but especially for the determination of proper motions."

As 838 stars occupy 401 pages, an average of about half a page is devoted to each star. A translation of the matter given for a sample star, SS Cassiopeiae, follows, which will give a better idea of the work than a verbal description.

3. SS Cassiopeiae ($0^h4^m24^s +51°0.6$). Not found in the B.D.

Position determined by Hartwig (*V.J.S.*, **43**, 72). Chart by Hartwig (*Bamb. Veröff.*, II, Band 1, 7).

(* 11^m6 pre. 6^s, 2.8 S.—* 11^m4 fol. 3^s, 1.6 S.—* 11^m1 fol. 5^s, 3.3 S)

Discovered 1905 by Fleming on the Draper-Memorial plates (*Harv. Circ.*, **98**). Spectrum Md. A range of photographic magnitude from 9^m0 to 11^m5 was found on 5 chart plates between the years 1898 and 1902. Variability confirmed by Seares and by Hartwig. From photometer measures in 1905 and 1906 Seares deduced the approximate elements: Max. $= 1905$ Aug. 24 (2417082) $+141^dE$. He found the visual range to be about 3 magnitudes, the light-curve nearly symmetrical about a sharp maximum. Hartwig found from observations between 1906 and 1910 a value of 139^d6 for the period, with a range between 8^m5 and 11^m7.

Literature.—Pickering, Notice of Discovery by Fleming (*Harv. Circ.*, **98**, and A.N. 4027).—Seares, 2 Max. 05 Aug. 24 (8^m0) and 06 Oct. 20 (8^m7) from photometer measures 05 Aug. 7 to Sept. 19 and 06 June 11 to 07 March 1. Statement of days when the variable was at or below the limit of the $7\frac{1}{2}$-inch equatorial. Approximate elements (*Laws Bulletin*, 10).—Hartwig, Individual Estimates and Deduced Magnitudes on 18 Days in the Years 1906–1910. 3 Max. 06 Oct. 20: (8^m5), 07 March 5: (8^m5), 07 July 20 (8^m5) and 2 Min. 07 Oct. 3 (11^m7), 08 July 1 (11.7). Chart of the neighboring stars (*Bamb. Veröff.*, II, Band 1, 7. See also A.N. 4212, Notation).—Graff, 4 estimates 06 July 29—07 Sept. 1, color 7, first and last estimates near the Min., third near the Max. (A.N. 4719). Color-estimates from 2 observations 6.0 (A.N. 4709).

The typography, as might be expected, is excellent. A single detail perhaps merits criticism, the use of lower case superior *m* (^{m}) to denote both minutes of right ascension and magnitude, frequently on the same line.

J. A. P.